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Radiometric Apparatus for Use in Psychological and Physiological Optics

Including a Discussion of the Various Types of Instruments that have been used for Measuring Light Intensities

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PREFACE

Six years ago, realizing the fundamental relation of energy measurements to quantitative work in psychological optics, we undertook to procure a non-selective radiometer which not only would be sufficiently sensitive for work in the visible spectrum, but the operation of which would be within the technical possibilities of the laboratories in which research is done in psychological optics. At that time we decided upon an instrument of the surface type because (a) we wished to measure all of the light falling on the opening of our campimeter screen rather than compute it from several measurements with the linear type of instrument; and (b) we believed that sensitivity would be added to the instrument in some proportion to the increase in area of the receiving surface (see this paper p. 12). A quick acting surface thermopile, because of its superior steadiness and ease of operation, seemed to be best adapted to our purpose. Since such an instrument could not be obtained in the market, Dr. W. W. Coblentz of the radiometric division of the Bureau of Standards who had at that time just finished a comparative study of the radiometric instruments showing the above-mentioned advantages of the thermopile, undertook the design and construction of the thermopiles, surface and linear, and the auxiliary radiometric apparatus which we have used in our work. These thermopiles are the first of their type made by Dr. Coblentz (see Bulletin of the Bureau of Standards, 1913, *9*, pp. 15-29) and have been used by us for five years. Thermopiles of this type are now in use also in many physical laboratories and in other laboratories in which a sensitive and convenient means is needed for measuring spectrum energies.* We

*For example, the recent work of Nutting (Phil. Mag., 1915, *29*, (6), p. 301), Ives, Coblentz and Kingsbury (Phys. Rev., 1915, *5*, (2), p. 269), and Coblentz and Emerson (Bull. Bur. of Standards, 1917, *14*, p. 167), on the visibility of radiation and the mechanical equivalent of light, of interest to psychologists, has been done and was made conveniently possible by these improved thermopiles designed and constructed by Dr. Coblentz.

are not thus recommending in the following pages an apparatus the feasibility and convenience of which for quantitative work of the kind needed in psychological optics is untried.

Of late some dispute seems to have arisen with regard to the need and uses of energy measurements for work in psychological optics. A brief discussion and statement of opinion on this point was given by us in an article published in the American Journal of Psychology in 1912. (A Note on the Determination of the Retina's Sensitivity to Colored Light in Radiometric Units, 23, pp. 328-332.) Time alone can of course reveal the full range of needs and uses of this type of measurement and render a just verdict on disputed points. A few words in the way of general perspective, however, may not be out of place here.

Considered in its relation to the eye two points of view may be recognized in the rating of lights. One of these is involved in their rating for the use of the eye as an organ of seeing. In such a rating it is obvious that the method used should take into account all of the eye's deviations from equality of response to the different wave-lengths of light. In the production of illuminating effects this is the work of photometry which should be done by the eye or some instrument calibrated to give results in terms of the responses of the eye. Another and quite different point of view, however, is involved in their rating for the purpose of investigating the eye's peculiarities or characteristics of response in every way in which it is capable of giving response. In such work it is obvious that the ultimate method of making the rating should be free from the peculiarities to be investigated, that is, should not be made by the eye itself. In general in work of this kind two needs arise. (1) A method of specification is required that will make possible an accurate and convenient reproduction of intensities from time to time and from laboratory to laboratory. The difficulty of doing this by photometry with lights differing widely as to wave-length as do in most cases the stimuli employed in psychological optics, is too well known to need emphasizing here. Obviously what is needed for certitude in this work is a measuring instrument

which can be calibrated directly against the standard of radiation, or black body, and which is non-selective in its response to wave-length,—not an instrument like the eye, the selenium cell, the photo-electric cell, or the photographic plate, the responses of which are not only selective to wave-length but vary in their amounts of selectiveness with change of intensity of light, differ greatly in both of these regards (especially the eye) from instrument to instrument or from sense organ to sense organ, and can be calibrated against the radiation standard or black body, if at all, only with a great deal of difficulty and with many chances of cumulative error.

The insistence on a subjective method of rating for standardizing purposes when the objective method is available, is not only difficult to understand but is entirely contradictory to current practice in other sense fields. No one would think, for example, of specifying for the purpose of securing reproducibility, the weights used in an investigation of skin sensitivities in terms of the skin's own responses when the means of making the physical measurement is at hand; yet there should be more chance of successfully establishing from laboratory to laboratory a system of calibration of skin measurements in terms of some common standard than there is of accomplishing the analogous task in case of light. It is scarcely conceivable that the most ardent advocate of subjective ratings in case of light would recommend the substitution of the subjective for the objective method for work on the skin for the simple reason that it would be so undesirable as not to be tolerated, unless for want of an objective method it was rendered absolutely necessary. With the objective method available from the beginning, the possibility of using the subjective method has not even been raised in work on the skin. And indeed the subjective method has been used in rating light intensities only because (a) for more than a hundred years no other method was available, and (b) it was desirable to rate lights for use in seeing by a method which gave results corresponding to the eye's powers of response. The former of these reasons for its use has now disappeared. Only the latter, with a few laboratory exceptions, remains and marks

off for the subjective method of rating, a separate and special field which is clearly recognized as such by physicists and the engineers dealing with the problem of lighting.

As a brief, however, for the continuation of the use of the eye for the measurement of its own stimuli, although such measurements would not be subjective, it may be claimed that in time it will be possible to calibrate the eye by means of the non-selective radiometers so that it can be used to measure the visible energies directly. For example, just as it is possible to measure a linear dimension with a meter rod and to convert the results into terms of the English system, and *vice versa;* so it may be possible to measure the different wave-lengths of light by the eye and convert the results obtained into energy values. The difficulties in the way of this, as we have already pointed out, consist in differences in the sensitivity of different eyes for a given wave-length; the selectiveness of the eye's response to wave-length and to intensity and its variations in both of these regards from observer to observer; the lack of a fixed scale from observation to observation, even in the case of a single observer; etc. In short to complete the analogy suggested above, it would be an exceedingly difficult task to convert measurements from the metric into the English system and *vice versa* if very few of the measuring rods employed represented the same amounts of linear space; if in case of a given rod the dimensions of some objects were over-estimated and others under-estimated and the magnitude of this over-estimation and under-estimation varied with the dimensions of the object measured by amounts as yet undetermined; etc.,—as happens in case of the eye's evaluations of the wave-lengths of the visible spectrum. Obviously if the eye's ratings are to be converted into energy values, it can come only after a very great deal of investigation and calibration against radiation standards by means, for example, of the non-selective radiometers, which but constitutes one of the subdivisions of what we have included under the second of the needs we are giving for energy measurements in the study of the responses of the eye. However, to represent the calibration as now completed and available for use instead of scarcely begun,

would be chimerical and visionary to a degree which we can consider compatible only with an insufficient knowledge and understanding of all that is involved in the problem.

Since the foregoing was written, Troland (Journal of Experimental Psychology, 1917, *2*, pp. 7-13) has advised that, instead of the thermopile or other non-selective radiometer, the psychologist may, with sufficient accuracy for his purpose, use the eye as a selective radiometer and convert the results into units of energy by means of a value for the mechanical equivalent of light that has recently been determined by Nutting (Philos. Mag., 1915, *29*, (6), p. 301). This point can not be discussed here in detail. We would, however, recommend that the reader consult this work on the mechanical equivalent, which has been done by means of the flicker photometer and the thermopile, and judge for himself how unreliable it would be to attempt to follow Dr. Troland's advice and use a result obtained with a given limited group of observers for only one intensity of light, to convert the photometric results of individual observers in other laboratories and for other intensities of light into anything at all closely approximating the correct energy values. It is obvious that in order to make the conversion in any given case with the same order of accuracy with which the direct energy measurements may be made, the same observers would have to be used, the same state of adaptation and sensitivity of the eye, the same intensity of light or approximately so (at least so far as adequate proof to the contrary for a large part of the intensity scale is concerned), the exact same range of wave-lengths and distribution of energy within the group of wave-lengths, and the same degree of purity of light as were used in making the original determination of the visibility curve which is meant to serve as the basis for making the conversion. Considering the first of these points alone, it will be remembered that Ives, working through the spectrum with the flicker photometer, found in a group of eighteen observers disagreements as great as 159 per cent for .487μ; 114 per cent for .498μ; 26 per cent for .518μ; 18 per cent for .537μ; 13 per cent for .556μ; 10 per cent for .576μ; 28 per cent for .595μ; 65 per cent for .615μ; 86 per cent for .635μ; and 122 per cent for .655μ. (Philos. Mag., 1912, *24*, Ser. 6, pp. 856-863.) From this showing of low agreement from observer to observer with the flicker photometer, it is clear that the results for individual observers could not be used for the purpose of making the conversions recommended unless some means were had of correcting these results to those of the group for which the original visibility curve and the mechanical equivalent were determined. Space can not be taken here to discuss the complications and approximations that would be involved in making such a correction. It will be sufficient to say that if it were made in the most approved manner—an adequate method of doing it has not by any means as yet been devised—and the mechanical equivalent were applied, the results would scarcely be accepted as correct even by an ordinarily careful worker unless they could be checked up by a direct energy measurement. In this connection it is interesting and important to note that the visibility curve as determined by Nutting does not agree with that determined by Ives, also that the curves of Nutting and Coblentz agree only when certain

corrections are made in the energy measurements of Nutting. In short the attempt to get a set of figures that will express for the different wave-lengths the relation of the lumen as evaluated by a number of eyes to the watt is an interesting bit of work and may present, perhaps, when the proper computations are made, a rough analogy to the determination of the mechanical equivalent of heat; but the attempt to use these figures to convert the photometric results of the individual observers in the different laboratories into the correct energy values is quite a different matter, and can scarcely be considered as the intent of those who have made the determination. This question will be discussed in greater detail in a later paper.

However, the idea of using the eye indirectly to determine the energy values of light is by no means new. Before the direct type of measurement had been made as feasible as it now is, several attempts were made to use the eye for this purpose. (See, for example, Lummer and Pringsheim. Jahresber. d. Schles. Ges. f. vaterl. Kultur, 1906, pp. 95-97; Beibl., 1907, p. 466; Thürmel, Das Lummer-Pringsheimsche Spektral-Flickerphotometer als optisches Pyrometer, Ann. der Phys., 1910, *33*, (4), pp. 1139, 1160; etc.)

(2) The second and perhaps more fundamental need for energy measurements for work on the eye is, as stated in the general heading, for a method of rating the stimulus which will make possible a quantitative comparison of the eye's power of response to its stimuli in every way in which it is capable of giving a response; for we can know the kind and amount of its selectiveness of reaction to the different wave-lengths of light only when they are compared with those of an instrument as standard which shows equal power or capacity of response to all wave-lengths. Only with such an instrument, or rather with such an evaluation of the stimuli as a common or invariable standard to which to refer the eye's evaluations or responses, can the work of comparing its powers or peculiarities of response to its stimuli be put on a basis that can be called quantitative for a single eye or from eye to eye. To this it may be demurred, however, that in some problems it is required as one of the features of the investigation that the stimuli have equal power to arouse the eye's response or sustain some subjective relation to each other. This need we have always freely recognized both in our work and in our recommendations. (See Amer. Jour. of Psychol., 1912, *23*, pp. 328-332.) It in no way conflicts with, however, or supplants the more fundamental one already given, but is rather supplementary to it in certain types

of investigation; for even in the cases where the subjective relation is demanded to fulfill the requirements of the investigation there is still great need for the ultimate purposes of the science that the physical amounts of light required to produce this subjective relation for the given observer be determined and specified. Again to use the analogy of work on skin sensation, it would be a careless investigator indeed who would fail to specify, if it were possible to do so, the physical measure of the weights he used to give, for example, equal pressure responses. In short, it seems a paradox that one should even feel the need to make a special pleading for the introduction of objective measurements into the work of psychological optics when it is the current practice to use objective ratings of the stimulus in every other field of psychological investigation in which it is possible to do so, the intensity ratings in vision and audition alone being the conspicuous outstanding exceptions and these being so only because adequate methods for making such ratings have been slow in coming.

As examples of needs for regulating the stimuli to give certain subjective relations we may quote here the following cases that we have already formally recognized. In a recent investigation of the comparative lags of the achromatic response to wavelength made in our laboratory, the stimuli employed were made photometrically equal and the amounts of light used to give these equal responses were measured radiometrically. The photometric equalizations were made because the data were wanted in an interpretation of the characteristic overestimations and underestimations found in the results of certain observers in photometry by the method of flicker as compared with their results by the equality of brightness method. In another investigation now in progress, namely, a determination of whether stimuli which have the same power to arouse the achromatic response have also the same power to make the eye lose in its capacity to give this response as a result of prolonged stimulation, the stimuli are as a matter of course being made subjectively equal as one of the essential conditions of the investigation; but again the amounts of light required to produce this subjective re-

lation will be determined radiometrically for the purpose of ultimate specification. Also in our original note on energy measurements we recognized quite broadly the possible need of establishing subjective relations between the stimuli used. For example, on p. 329 in discussing methods of determining after-image and contrast sensitivity, we state: "It is conceivable that two points of view may be held with regard to what is meant by after-image and contrast sensitivity. (1) After-image and contrast sensitivity may express a relation between the amounts of light required to arouse after-image and contrast sensations and the unit of light used. (2) It may express a relation between the amount of light required to arouse the after-image and contrast sensations and the amount required to arouse the positive sensation." In the former case the after-image or contrast sensations are treated as one of the eye's responses the selectiveness of which to wave-length is to be determined; in the latter a figure is sought which expresses the relation between the after-image and contrast and the positive sensitivities. On the same and the succeeding page we say: "Similarly two views may be held with regard to the determination of the comparative rates of fatigue, and of the development-time of sensation. (1) Lights equalized in energy may be used. (2) The energy of the lights may be made proportional to the sensitivity of the eye to the different colors." Also in discussing the investigation of the peripheral limits of sensitivity, we state: "(a) The limits may be considered in relation to the comparative sensitivity of the retina to the different colors. (b) They may be considered in relation to existing color theories. In the first of these problems the limits should be obtained with stimuli equalized in energy. So obtained the results will constitute merely another expression of the comparative sensitivity of the retina to the different colors. The second problem is more complicated and will be made the subject of a separate paper." Indeed as these citations abundantly show, we have never failed to recognize that the stimuli in certain types of investigation must be made to conform to some type of subjective relation, but these investigations constitute in immediate importance only a minor part of the

work that is to be done in getting a thorough knowledge of the eye's characteristics of response; and even in these investigations there is as great need of an invariable standard of reference as there is in any field, psychological or otherwise, where the value of quantitative work or measurement is recognized.

Perhaps the general character of the discussion will not be deviated from too widely if we add in conclusion a word on the determination of retinal sensitivities which will indicate in a concrete case the type of treatment that should in our opinion be given both to the response and to the stimulus, when possible, in quantitative work in psychological optics. If the sensitivity of the retina is to be measured in a way that is comparable with the measurement of the sensitivity of the physical recording instruments, two conditions must be fulfilled: (a) the amounts of response in terms of which the comparison is to be made must be numerically comparable; and (b) the amounts of stimulus used in arousing the response must also be numerically comparable, or commensurable. The sensitivity of two galvanometers could not be compared, for example, were it not known that the divisions on the scale of each were either equal or commensurable; likewise the amounts of current used to produce the given deflections must be known in terms of the same, or comparable units. With the introduction of the radiometric treatment of the stimulus the second of the above conditions is fulfilled, and for the first time in a way that can be considered as quantitative to a degree that would be acceptable in the rating of the sensitivity of a physical instrument. With reference to the first condition we are confronted with a situation somewhat similar to that which obtains in heterochromatic photometry. That is, in general five different quantities have been used or suggested in the work of measuring sensitivities (the liminal threshold, the just noticeable difference, the average error, equal amounts of response and equal sense differences), but only the last two of these, so far as has yet been demonstrated, conform with certainty to the requirement that is considered absolutely necessary in determining the sensitivity of a physical instrument, namely, that the amounts of response as well as the amounts of

stimulus must be numerically comparable. Moreover, in the absence of sureness of principle in case of the other three, the empirical check of agreement in result with those that have the needed sureness of principle has never been offered; yet sensitivities are determined just as if this condition did not exist, comparisons are made and conclusions are drawn. In short it may not be out of place to call attention here to the looseness of thinking and practice that prevails more or less generally with regard to the work of determining physiological sensitivities as compared with the analogous physical determinations. For the sake of consistency it might well be urged either that this work be revised on the basis of the standards set for the physical instruments with all of the interchecking of methods that is needed, or that the term sensitivity with its definite quantitative connotation be abandoned in all cases in which this standard can not be lived up to.

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I. INTRODUCTION

In a previous paper the purpose has been expressed of describing apparatus for work on the color sensitivity of the retina consisting of spectroscopic and radiometric features. In partial fulfillment of this purpose apparatus was described in a recent number of the Journal of Experimental Psychology[1] designed to meet the following needs: (1) to stimulate any part of the retina with the light of the spectrum and to control as desired the conditions of preexposure and surrounding field; and (2) to regulate the amounts of light used within the small gradations needed for threshold and just noticeable difference determinations. It is the purpose of the present paper to describe apparatus with which it is possible to specify the amount of light used in energy units. This completes the description of a group of apparatus by means of which it is possible to determine the sensitivity of the eye to wave-length in terms that are commensurable, and thus to place the investigation of the responses of the eye on a methodological plane comparable with the study of the responses of the physical recording instruments. This could not be done until a means was had of estimating light intensities which is not only independent of the achromatic and chromatic functioning of the eye itself, but which gives results directly proportional to the physical value or energy of the light waves. An instrument which gives responses directly proportional to the intensity of the light-waves is, we scarcely need to point out, equally sensitive to all wave-lengths. With the responses of such an apparatus as standard, the deviations of the eye from equal sensitivity to the different wave-lengths can readily be determined and compared.

[1] Ferree and Rand. A Spectroscopic Apparatus for the Investigation of the Color Sensitivity of the Retina, Central and Peripheral. J. of Experimental Psychology, 1916, *1*, pp. 247-283.

II. METHODS AND APPARATUS THAT HAVE BEEN USED FOR THE MEASUREMENT OF LIGHT INTENSITIES AND THEIR APPLICABILITY TO THE INVESTIGATION OF RETINAL SENSITIVITIES

No problem in optics probably has presented more difficulty to the investigator and the various committees which have been appointed for the purpose by scientific and engineering societies, bureaus, etc., than that of standardizing the intensity of lights differing in color value. In the investigation of retinal sensitivities the problem of standardizing presents two aspects. (1) As the prime requisite of scientific work a method of specification is needed that will make possible an accurate and convenient reproduction of light intensities. Without this no investigation can have the certitude that comes from repetition and verification. And (2) an important item in the determination of retinal sensitivities has been a comparison of the sensitivity to different wave-lengths. This has been made a feature of the general problem for the sake both of knowing the characteristics of the eye as a sense-organ and measuring instrument, and of being able to meet the many practical needs that have arisen in the attempt most effectively to adapt light to the service of the eye in the work of lighting, etc. As we have already pointed out, if the sensitivity or responsiveness of the eye to lights of different wave-lengths is to be compared, it is obvious that a common unit must be had, independent of the functioning of the eye itself, in terms of which to measure the quantity or intensity of the light employed; or to express the need in another form, the light to be used in the investigation should be rated by instruments whose responses are directly proportional to the energy value of the light waves.[1] Such instruments being non-selective in their response to wave-

[1] For a further statement of the conditions that must be fulfilled if the sensitivity of the retina is to be measured in a way that is comparable with the measurement of the sensitivity of the physical recording instruments, see Preface, p. xi.

length and giving the true physical value of the stimulus are the logical standard of reference in the comparative study of instruments or organisms whose responses are selective. Fortunately instruments for measuring light intensities which fulfill the above requirements have within the last few years reached such a stage of advancement as to make this kind of treatment of the problem not only possible but feasible and even convenient. On this account a brief history may not be out of place here of the attempts that have been made to attain measurements of light intensities which are purely physical.

Light of any wave-length is universally conceded to be a form of motion in a transmitting medium. By common agreement among physicists quantitative estimates of motion are made in terms of what is called energy of motion; or of mass and rate of motion. Owing to the small quantities of energy involved in the waves of the visible spectrum, it is obvious that light energies can not be estimated directly in terms of mass and rate of motion. Some instrument or apparatus which responds to light must be used and the response of this instrument be calibrated against a source of energy the radiation from which per unit of surface per unit of time is known. Once calibrated, such an instrument with proper checks on its sensitivity may be used for the measurement of the visible radiations from any source. The requisites of a satisfactory instrument for the physical measurement of light are obviously as follows. (1) It must give a response which is directly proportional to the energy of the light wave or must be capable of calibration against an instrument which does give such responses. (2) It should be non-selective in its response to wave-length and to intensity, *i.e.*, it should be no more sensitive to one wave-length of the spectrum than to another and its sensitivity should not vary with the intensity of the light used. This requirement is an obvious corollary to the preceding. If an instrument is used which is selective in its response to wave-length, the amount of its selectiveness must be a constant else correction factors cannot be determined which will be valid for all intensities. (3) It should be sufficiently sensitive to respond to the small amounts of light present in the visible spectrum. And (4) it

should give results which have a satisfactory degree of reproducibility, or if erratic within known limits or conditions it must be calibrated against some instrument which does give reproducible results, and correction factors be determined.

As comparators of light intensities the following instruments and the human eye have at various times been employed or investigated,—the Nichol's radiometer, the radio-micrometer, the micro-radiometer, the bolometer, the thermopile, the selenium cell, the various types of photo-electric cell, and the photographic plate.[2] The following comparisons may be made of these instruments with regard to the above mentioned requirements. (a) The radiometer, the radio-micrometer, the micro-radiometer, the bolometer, and the thermopile, depending initially for their action on heating effects, give responses which are directly proportional to the energy of the incident light. They are, therefore, non-selective in their reaction both to wave-length and to intensity.[3] The selenium cell, the photo-electric cell, the photographic plate and the human eye, however, do not give responses which are proportional to the energy of the incident light. They are all known to be selective in their reaction to wave-length; and the amount of this selectiveness in case of the selenium cell, the photographic plate and the human eye has been found to change with the intensity of light. (b) All the instruments which are selective in their responses to wave-length, namely, the human eye, the selenium cell, the photo-electric cell and the photographic plate, have a high degree of sensitivity to light. The photographic plate possesses the additional advantage that the action may be integrated over an interval of time. The instruments which are non-selective to wave-length are as a class less sensitive to light. Recent improvements in the construction of such instruments,

[2] The use of these instruments for the measurement of light is based on the following effects produced by incident light: (1) heating effects; (2) a change in the resistance of certain metals to the flow of a current; (3) a decrease in the power of certain metals to hold a negative charge in a partial vacuum; (4) chemical action; and (5) visual sensation,—used chiefly in connection with the various types of photometer.

[3] It should be mentioned, however, that their windows absorb selectively some of the wave-lengths of the invisible spectrum.

however, have increased their sensitivity greatly. Of this class of instruments, the thermopile because of its greater ease of control and greater reliability is probably best adapted for use in laboratories of physiological and psychological optics. Moreover, as was stated in our introduction, it has been developed to a high degree of sensitivity. In fact a comparative study of the non-selective instruments has shown that in the present stage of development of such instruments, the thermopile possesses as high a sensitivity as the others when operated in air and probably also when operated in a vacuum. (c) The factors which influence the response and use of the instruments which are selective in their action to wave-length have proven to be so hard to control that the results obtained have shown a comparatively low degree of reproducibility. Of the non-selective instruments the bolometer is perhaps the hardest to control. The factors which influence the action of the thermopile, the radiometer, and the radio-micrometer are on the other hand comparatively easy to control. A comparative statement of the advantages and disadvantages of these instruments will be given later in the paper.

Before considering these instruments in greater detail, it may be of service perhaps to give a brief statement of the type of action that is produced in each by the radiant energy falling upon its receiving surface. As was stated earlier in the discussion, the measurement of energy by the types of instrument that are mentioned here is not direct. The instrument is available because it gives to a greater or lesser degree some regular and constant type of response to radiant energy, the value of which in energy units is determined by calibration against the known radiations from a black body, or from some other source whose radiations have been determined by comparison with that from a black body. In instruments of the type of the radiometer, micro-radiometer, radio-micrometer, bolometer and thermopile, all radiations are transformed into heat at the receiving surface of the instrument. In case of the radiometer, for example, the absorbed energy produces thermodynamic effects in the rarified gas contained in the housing of the instrument, which in turn causes regular deflections of a delicately suspended vane; in case of the radio-microm-

eter and the thermopile, the absorbed energy acting upon a thermo-electric couple causes a flow of current which deflects the needle of a sensitive galvanometer in circuit with it; and in case of the micro-radiometer and bolometer, the absorbed energy changes the resistance to the flow of current in a delicately balanced electric circuit which is also detected by means of a sensitive galvanometer. The action of the remaining instruments is not due to heating effects; also these instruments are not responsive to all radiations. The selenium cell and the eye, for example, are sensitive only to the visible spectrum (Brown and Sieg, however, Phys. Rev., 1914, *4*, (2), pp. 48-61, report one cell that has considerable sensitivity as far out as .85μ.) the photographic plate, when properly sensitized to red, and the photo-electric cell are sensitive both to the visible and the ultra-violet radiations.

In case of the selenium cell the visible radiations falling on a strip of metallic selenium placed in one arm of a delicately balanced electric circuit so change the resistance of the selenium to the flow of current that the electromotive balance between the two arms of the circuit is disturbed, and a flow of current takes place between two given points which were before at equal potentials. This current deflects a galvanometer. The use of the selenium cell is attended with a great deal of difficulty and there are many opportunities for cumulative error. The following is a brief statement of some of these difficulties. A detailed statement will be given later in the paper. (1) As an instrument to be used in the process of measuring, it can be employed without calibration (*e.g.*, the determination of sensitivity curves for different intensities of light expressing a relation between response and energy) only to identify equal amounts of energy; and since it is as a general case responsive only to light waves it can be used to equalize only light energies. Its employment in this way as a measuring instrument for the visible spectrum energies presupposes, therefore, a standard light source, the energy values of the visible spectrum from which are known, against which to balance the unknown lights. But as stated earlier in the paper, the light energy emitted from sources ordinarily available can not be determined directly. It must be determined by compari-

son with the radiations from some body the amount of which can be directly estimated. This comparison may be most conveniently made by means of some measuring instrument such as the thermopile which is responsive to the total of radiation and which is non-selective in its response to wave-length, and a black body radiating known amounts of energy to furnish the standard for the comparison. In short, without the possibility of ultimate recourse to such instruments as the thermopile, the radio-micrometer, etc., which are non-selective in their response to wave-length, instruments of the class of the selenium cell would be practically useless for radiometric purposes. Moreover, the two-fold nature of the measuring operation, the difficulty of maintaining constancy of conditions in the employment of the secondary standard, and more especially the many factors extraneous to light which influence its response, make its use very liable to error. And (2) since the selenium cell is selective in its responsiveness to the different wave-lengths of light, the standard light source must in every case be of the same spectro-radiometric composition as the light against which it is to be balanced, otherwise the cell can not be relied upon to give to the unknown light a fair radiometric evaluation. That is, if the light to be measured is not of the same wave-length or composition as the standard light, correction factors have to be used which represent the amount of the selectiveness of action. Furthermore, the amount of selectiveness of the action changes with the intensity of light, therefore correction factors established for one intensity will not serve for all intensities.

The action of the photo-electric cell depends on the power of light to cause certain metals to lose a negative charge of electricity in a partial vacuum. Much that has just been said of the selenium cell applies also to the photo-electric cell. (1) It is not sensitive to the infra-red spectrum, hence can not be calibrated directly against the total of radiation of a black body. (2) It is selective in its response to the different wave-lengths of the visible spectrum. Griffith and Dember claim that it is also selective to intensity. (3) Its use in measuring the energy of the visible spectrum presupposes, for example, either some calibration similar

to that noted above for the selenium cell, or the availability of a light source the values of the visible radiations of which are known to serve as a standard against which to balance the unknown wave-lengths. And (4) its sensitivity is influenced by so many factors difficult of control as to give it a comparatively low reproducibility of response.

The photographic plate responds to light by a chemical change in its sensitive film, known as the 'blackening" of the plate. Its convenient use as an energy measuring instrument depends upon whether or not this blackening sustains any constant relation to the amount of incident light. If not, its use would necessitate such an elaborate calibration as to render it impracticable as a radiometer. Like the selenium and photo-electric cells, it too is selective both to wave-length and to intensity; its employment as an energy measuring instrument presupposes a standard light source, the energy value of the radiations from which is known; and its responses are subject to the influence of many variable factors which tend to give them a low degree of reproducibility.

The eye gives two responses to light waves, the chromatic and the achromatic. As yet the achromatic response alone has been used in the measurement of light intensities. Two possibilities are presented for the use of the eye as a measuring instrument: photometric or the rating of lights in terms of their power to arouse the achromatic sensation; and radiometric in the sense of balancing or equalizing the energy values of lights of the same spectro-radiometric composition. As an energy comparator the eye is like the selenium cell in the following regards. (1) It is responsive only to the visible spectrum. Its employment, therefore, presupposes the provision of a light source, the energy value of the visible radiations from which are known. And (2) since it is selective in its response to wave-length, it can without correction factors be used to establish an energy balance only between lights having the same spectro-radiometric composition. While not generally used or classed as radiometric, the eye can like the selenium and photo-electric cells be used very sensitively to balance energies of lights of the same spectro-radiometric

composition and has in this respect a similar claim to be considered as one of the radiometric possibilities. In fact our control of the factors which influence the response of the eye is perhaps enough greater than that of the selenium cell, the photo-electric cell, etc., to render its use for this purpose preferable from the standpoint of precision.

A. The Thermopile.[4]

The thermopile is probably the most celebrated of the radiometric instruments. To it we are indebted for the researches of Melloni and Tyndall as well as for the most notable advances that have been made in the study of radiation. The instrument was invented by Nobili and is based on a discovery made by Seebeck about 1820 that when two wires of different metals are joined end to end so as to form a closed circuit, an electric current passes around the circuit when one of the junctions is heated or cooled, and this current continues to flow as long as any difference of temperature exists between the two junctions.[5]

[4] With regard to the non-selective radiometers we are indebted heavily to the publications of Dr. Coblentz for data and for guidance in the compilation of data.

[5] There are three thermo-electric effects in metals: the Seebeck effect, the Peltier effect, and the Thomson effect. The Seebeck effect is described above and is the one on which the action of the thermopile is based. The Peltier effect discovered in 1834 is the converse of the Seebeck effect, *i.e.*, when a current is passed through a junction of dissimilar metals, the junction is either heated or cooled depending upon the direction of the current with reference to the thermo-electric relation of the metals. For example, if the current passes from the electro-negative to the electro-positive, work is done and the temperature of the junction is raised; but if it passes from the electro-positive to the electro-negative, the temperature of the junction is lowered. The result of the Peltier effect in a thermo-couple, therefore, is to lower the temperature of the exposed junction. This effect, however, is not considered to be sufficient to make an appreciable change in the results gotten with a thermopile-galvanometer combination of the sensitivity ordinarily obtained. The Thomson effect is a heat effect manifested when a current flows between points at different temperatures in the same metal. This effect differs in different metals. For example, when a current flows from a hot to a cold point in copper, it evolves heat; but when it flows from a cold to a hot point, heat is absorbed. In iron, however, the reverse is true. When the current flows from a hot to a cold point, heat is absorbed. This effect for the small temperature differences involved is also considered negligible by Altenkirch (Phys. Zeit., 1909, *10*, p. 560) in his discussion of the efficiency of thermopiles.

Like the bolometer the thermopile owes its effective sensitivity in part to its own construction and in part to the auxiliary galvanometer.

1. *Important points in the construction of sensitive thermopiles.* The problem in thermopile construction appears to be to secure a low resistance, a low heat capacity and heat conductivity, and a high thermo-electric power. The following have been found to be important points in the construction of thermopiles. a. *The metals used to form the thermo-electric junctions.* This point is of importance because metals are found to differ in their thermo-electric power, *i.e.,* in their electromotive force per degree centigrade when compared with the standard metal, lead. The following are some of the thermo-electric metals: bismuth, silver, German silver, lead, platinum, copper, zinc, iron, antimony, constantan, tellurium, and selenium. A very small amount of impurity may make a great difference in the thermo-electric power of a metal, and some of the alloys and metallic sulphides show a very high thermo-electric power. Some of the combinations most commonly used in making thermo-couples are bismuth and antimony, iron and constantan, and bismuth and silver. The bismuth and silver couple has been chosen by Coblentz because of its high thermo-electric power and low resistance. Silver was selected to complete the element with bismuth more especially because of its low resistance, its pliability and the ease with which it can be cleaned[6] and annealed. The latter two points are of great importance in the construction of the pile. Nicety of construction is of fact of greater importance to a high radiation sensitivity, Coblentz declares, than a high thermal E. M. F.[7] provided the material has a correspondingly high resistance.

[6] It is important that the metal chosen be easily cleaned for completeness of contact in soldering. A preliminary heating can be given the silver wire which serves the double purpose of cleaning and annealing. This preliminary heating could not, for example, be given to copper and iron wire.

[7] Coblentz (Bulletin of Bureau of Standards, 1914, 11, pp. 148-150) found, for example, in eight samples of bismuth wire with diameters of 0.06, 0.08, 0.1 and 0.15 mm. that the thermo-electric power when coupled with silver varied from 75 to 82 microvolts per degree, depending upon the purity of the material. Haken (Verh. Phys. Gesell., 1910, 12, p. 229) and Gelhoff and

b. *The size of the wire used in forming the couples.* The chief defects in the older types of thermopiles were their great heat capacity and their consequent lag in reaching a temperature equilibrium. The larger the wire used in making the couple, the greater, of course, will be the heat capacity. In the recent attempts that have been made to improve the linear thermopile a prominent item of change has been the use of finer wires, which not only decreases the heat capacity and lag and increases the radiation sensitivity, but permits more elements to be placed in a given area. The decrease in the size of the wire, however, increases the internal resistance which must of course be taken into account in planning for sensitivity. For example, Coblentz[8] found in experiments with surface thermopiles that a bismuth wire 0.15 mm. in diameter had sufficient heat capacity to require a half minute to attain thermal equilibrium, while a wire 0.1 mm. in diameter gave satisfactory results. Using this wire in conjunction with one of silver 0.0513 mm. in diameter as a standard of sensitivity, a silver wire of 0.041 mm. in diameter gave a sensitivity of 1.13; one of 0.03 mm. in diameter, a sensitivity of 1.20; and one of 0.021 mm. diameter, a sensitivity of only 1.12. That is, when the wire has reached an optimum fineness, any further decrease in size so increases the internal resistance as to more than

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Neumeier (*ibid.*, 1913, 15, p. 876) found that an alloy of bismuth with 9 to 10 per cent antimony gives a thermo-electric power which varies from 77 to 87 microvolts. Coblentz (*Op. cit.*, p. 149) found that an alloy of 5 to 6 per cent of tin gives a thermal E. M. F. of —44 to —45 microvolts per degree; and a thermo-element made of high grade bismuth and this alloy gives a thermo-electric power of 125 to 127 microvolts per degree.

While having 50 to 60 per cent higher thermo-electric power than a bismuth-silver pile, piles made of the bismuth alloy showed only about 10 per cent higher radiation sensitivity. The alloy is so much harder to handle that the same nicety of construction is not possible, also as high a durability is not attained. Since in making the silver-bismuth couple a bead of tin is used in soldering the two wires together, an alloy of bismuth and tin is made at the junction.

A bismuth-iron thermo-element (*op. cit.*, pp. 151-154) was found to give a thermal E. M. F. which was 18 per cent higher than was obtained from bismuth and silver. No increase of radiation sensitivity was obtained, however, because the initial resistance was almost doubled by the use of the iron.

[8] Coblentz, W. W. Bulletin Bureau of Standards, 1913, 9, pp. 21-22.

compensate for the advantage gained by the lessened heat capacity. Johansen further says[9] that the radii of the two wires of the thermo-element should be so chosen that the ratio between the heat conductivity and the electrical resistance is the same in both.

c. *The dimensions of the pile and the number and arrangement of the receiving thermo-couples.* In a recent theoretical contribution to the construction of thermopiles for the measurement of radiant energy, more especially the construction of vacuum thermopiles, Johansen[10] arrives at the conclusion that the radiation sensitivity is proportional to the square root of the exposed surface in case of the thermopile as it is in case of the bolometer. In extensive experimental determinations of the point, however, Coblentz[11] finds (a) that in single thermo-couples the sensitivity is not proportional to the square root of the area exposed to radiation, but that the area has an optimum value which gives a considerably higher sensitivity than is required compatible with the square root law; and (b) that the highest sensitivity is attained by building up a composite receiver of elements having individual receivers of a size giving the maximum sensitivity.[12] It is obvious, therefore, that sensitivity can be added to the instrument by increasing the total area of the receiving surface and consequently the number of thermo-couples, the individual receivers of which make up the total area; and that the maximum increase can be attained by having each individual receiver of the optimum size. In one of his more recent models of linear thermopiles

[9] Johansen, E. S. Ann. der Phys., 1910, 33, (4), p. 517.

[10] Johansen, E. S. *Loc. cit.*

[11] Coblentz, W. W. Bulletin of Bureau of Standards, 1914, *11*, p. 142.

[12] From the data obtained in constructing the receiving surface in this way, he concludes that the gain in sensitivity over what is indicated by the square root law amounts probably to as much as 50 per cent.

According to Coblentz the requisite of the optimum size is that it shall absorb radiant energy at a rate which will just compensate for the loss of heat from conduction along the wires. If this size is exceeded, the loss from emission becomes even greater than the loss by conduction along the wires and the two together operate to give less than the maximum difference of temperature attainable between the "hot" and "cold" junctions of the couple. A lag in reaching a thermal equilibrium also results because the heat is drained off from the center of the receiver faster than from the edges by conduction along the wire.

Coblentz[13] uses, for example, 22 junctions of bismuth and silver mounted in a space 10.5 mm. long. The width of this pile was 5 mm. and its resistance was 10.8 ohms.[14] In the surface thermopile greater sensitivity may of course be attained than in the linear. The surface pile is in effect built up of contiguous linear piles.

d. *The type of connection of the couples.* In the older types of thermopile it was the custom to connect the couples in series. Coblentz[15] has found, however, that it is of advantage to substitute a series-parallel connection. In the series connection one thermo-couple is attached to each of the overlapping receivers on the front of the pile, while in the series-parallel arrangement two couples are soldered to each receiver. The effect of this type of connection is in the first place to reduce the number of overlapping receivers by one-half. This reduces the superfluous metal at the lap and the amount of insulation required, and gives the apparatus a quicker response. And secondly the internal resistance is reduced to one-fourth what it would be if the elements were all connected in series; so that although their E. M. F. is reduced by one-half by the series-parallel arrangement, there is a gain of from 10 to 12 percent. in radiation sensitivity.

e. *The relation of internal to external resistance.* It has been a commonly accepted principle in the construction of thermopiles that the highest sensitivity is attained when the resistance in the thermopile is equal to the resistance of galvanometer and connecting wires. Rayleigh,[16] for example, in his computation of the thermodynamic efficiency of the thermopile has shown that the useful work done externally attains a maximum when the external resistance is equal to the internal resistance. In these computations only the specific resistances and the thermal conductivities were considered. Altenkirch,[17] 1909, however, contends that the

[13] Coblentz, W. W. Bulletin of Bureau of Standards, 1913, *9*, p. 292.

[14] The linear pile that has been used in the work that has been done in this laboratory is of this type with the exception that the receiving surface, designed for spectroscopic work, has a breadth of only 2 mm.

[15] Coblentz, W. W. Bulletin of the Bureau of Standards, 1914, *11*, pp. 138-142.

[16] Rayleigh. Phil. Mag., 1885, *20* (5), p. 361.

[17] Altenkirch, E. Phys. Zeit., 1909, *10*, p. 560.

external resistance may be two or three times the internal resistance without seriously affecting the maximum efficiency of the thermopile, and Coblentz,[18] 1914, finds that the external resistance may be two or three times the internal resistance without decreasing the sensitivity of the instrument more than 5 to 10 percent.

f. *Nicety of construction.* Coblentz makes the statement that the attainment of a high radiation sensitivity in a thermopile is at the present stage of development of thermopile making mainly a question of nicety of construction, for upon this more than any other point depends the low heat capacity, conductivity and emissivity needed for a sensitive instrument. The following are some of the points that should be taken into account in attaining the most effective relation between capacity, conductivity and emissivity,—the kind of materials, the size and form of the wires used for the couples, the length of wire, the size of the receiving surface, the type of connection of the couples, the relation of size of slit to size of receiving surface, the amount of insulation material, etc.[19] The object to be attained by a low heat capacity, conductivity and emissivity is of course that the energy falling on the receiving surface shall cause a maximum rise of temperature and that there shall be as little lag as is possible in the rise to

[18] Coblentz, W. W., *op. cit.*, p. 175.

[19] Coblentz attributes a great deal of his success in the construction of thermopiles to the use of his electrically heated welding device. (See Bull. Bureau of Standards, 1913, 9, p. 16); to the choice of silver wire which is easily cleaned and annealed; and to his use of pure tin in the process of welding which produces an alloy which is not brittle.

He cites cases to show the effect on sensitivity of deviations from the general method of construction. For example, the central line of receivers of one thermopile was given an additional coat of shellac to cause the individual receivers to adhere, instead of causing the adhesion by merely moistening the insulating layer with alcohol. The instrument was slow in responding to a radiation stimulus and was besides insensitive. This extra shellac was then removed by means of blotting paper wet with alcohol, and the surfaces resmoked. The radiation sensitivity was increased 40 to 50 per cent. In another case a thermopile was made of 0.1 mm. wire pressed flat. This thermopile had a radiation sensitivity 25 to 30 per cent less than the average sensitivity of a number of similar thermopiles made of round wire. The flat wire which presented a greater surface for radiation increased the emissivity and thus lowered the sensitivity of the instrument.

thermal equilibrium. When this is attained the instrument will respond quickly and give its maximum response.

g. *Provisions to secure steadiness of response.* The main source of unsteadiness of response is exposure to air currents. This of course can be completely eliminated by isolating the instrument from the air. The best success of isolation is evacuation which doubles the sensitivity. Water jackets and combinations of water and air jackets have been used also. Unlike the bolometer, however, the thermopile is noted for its steadiness of response in air. This is one of the strongest recommendations for its general use.

Older forms of thermopiles used by Melloni, Tyndall and others were subject to a "drift"; *i.e.,* there was a permanent E.M.F. which caused a permanent deflection of the galvanometer. This permanent E. M. F. seems at least in part to have been due to lack of symmetry in the construction of the "hot" and "cold" junctions. In our own linear thermopile this tendency to drift was overcome by soldering on the "cold" junctions receiving surfaces of tin of the same dimensions as were carried by the "hot" junctions.

2. *Advantages of the thermopile.* (1) It is non-selective in its response to wave-length. (2) It is readily portable and is easily adapted to the many needs for which a sensitive radiometer is needed. (3) In its most improved forms it is very steady in its action. Even when used in air there is comparatively little drift. (4) A high degree of sensitivity has been obtained. Coblentz[20] with a single thermo-couple in a vacuum and a 3-foot telescope has recently made quantitative measurements of the radiations of stars of the fifth magnitude and detectable responses were obtained from stars of the seventh magnitude. The instruments used by us are abundantly sensitive to measure the visible spectrum. (5) It is already attainable in forms adapted to special purposes. Coblentz[21] for example, describes thermopiles for the following purposes: for stellar

[20] Coblentz, W. W. Publications of the Astronomical Society of the Pacific, 1914, *26*, pp. 169-178.

[21] Coblentz, W. W. Bulletin of Bureau of Standards, 1914, *11*, p. 163.

measurements, and the measurements of other nocturnal radiations; for the measurements needed in physical photometry; for the determination of whether or not heat is generated in the tetanization of a nerve (an ingenious device in which the thermo-couple is made into a U-shaped trough for the reception of the nerve); and for various miscellaneous purposes which need not be gone into here. Its feasibility and wide range of utility are attested by the fact that it is now being used with success and a fair degree of convenience in radiation work in physical, chemical, biological and psychological laboratories. Owing to the recent improvements that have been made in its sensitivity, its quickness and steadiness of response, and the ease and convenience with which it can be operated, it seems to be the most promising of the radiation instruments now available, especially for the use of the experimenter who is not a radiometric specialist. These improvements mark, it is to be hoped, an epoch in the quantitative study of phenomena in the production of which radiation plays a part.

B. The Nichol's Radiometer

The radiometer was first described by Crookes[22] in 1874 as an interesting scientific toy. Some years later it was used in a somewhat modified form to investigate the infra-red spectrum to about 1.5μ.[23] The first really useful radiometer was developed by Nichols in 1896.[24] It was further developed and improved by Coblentz in 1905.[25] In its modern form the radiometer consists of two similar thin vanes of mica or platinum blackened on one side which are held together by glass fibres and are suspended in a vacuum by means of a fine quartz fiber. The vanes are about 3 mm. from an opening or window in the housing of the apparatus. The radiations to be measured fall upon one of the vanes which becomes slightly warmed. This

[22] Crookes, W. Philos Trans. 1874, *164*, p. 501; 1875, *165*, p. 519; 1876, *166*, p. 325.

[23] Pringsheim, E. Ann. der Phys. 1883, *18*, p. 32.

[24] Nichols, E. F. Berichte der Berliner Akad., 1896, p. 1186; Phys. Rev., 1897, *4*, p. 297.

[25] Coblentz, W. W. Investigations of Infra-red Spectra. Carnegie Publication, No. 35, Washington, 1905, p. 21.

causes the residual gas molecules to rebound with increased velocity from the blackened surface and the reaction pushes this vane from the window causing a rotation about the axis of suspension. A small mirror is attached to the glass fiber which forms the axis of rotation, and the deflection is observed by means of a telescope and scale.

1. *Significant points with regard to the radiometer.* The behavior of the radiometer has been worked out theoretically by Maxwell[26] in his paper on "Stresses in Rarefied Gases Arising from Inequalities of Temperature." Crookes, Nichols, and others have shown that the sensitiveness of the radiometer is a function of the pressure of the residual gas surrounding the vanes, of the kind of gas, and of the distance of the exposed vanes from the window. Investigation by Coblentz[27] has also brought out the following points. (1) For vanes of small dimensions such as must be used in practical work, the deflections are found to be proportional to the area of the exposed surface of the vane. (2) The sensitiveness varies with the diameter of the suspension fiber. (3) The instrument is not selective in its response.

2. *Comparative advantages and disadvantages of the radiometer.* As a working instrument the radiometer is said to have the following advantages. (a) Its sensitiveness is comparatively easy to control since it can be made to depend almost entirely upon the pressure of the residual gas. (b) It is not influenced by magnetic and thermo-electric disturbances which render work with a very sensitive galvanometer tedious and unsatisfactory. (c) It is not so sensitive to temperature changes as is, for example, a bolometer, and it can be more easily shielded from changes in temperature than can a bolometer with its galvanometer, battery, etc. It has the following disadvantages. (a) It is not portable, which may cause inconvenience in certain types of work. (b) For maximum sensitiveness its period is very long as compared with that of a bolometer or thermopile and galvanometer combination. (Nichols used a period of 8-12 sec., single

[26] Maxwell, J. C. The Scientific Papers of, *2*, p. 681; Philos. Trans., 1879, *170*, p. 231.

[27] Coblentz, W. W. Bull. Bur. Standards, 1907, 4, p. 405.

swing; Coblentz 30-45 sec.) This makes the instrument slow to operate. As a compensating feature, however, as Coblentz points out, the readings are always trustworthy so that there is no need to repeat them. (c) Its window or preferably double window is selective in its transmission in the invisible parts of the spectrum. A correction has, therefore, to be applied to the results for this inequality when working in this region.

C. The Radio-micrometer.

This instrument was invented independently by d'Arsonval[28] and by Boys.[29] It combines in one instrument the thermo-couple which in response to the radiant energy generates the electric current, and the galvanometer which indicates by its deflections the comparative amounts of current. That is, the radio-micrometer is essentially a moving coil galvanometer, the moving coil of which contains one or more thermo-junctions. In the instrument devised by d'Arsonval a single loop of wire was used, one part of which was silver and the other palladium. In the instrument devised by Boys the moving coil consisted of a loop of copper wire to which was soldered a thermo-junction of bismuth and antimony. These instruments not having been found to possess the sensitivity attributed to them by their inventors, various attempts have been made to improve them but with little success. Paschen,[30] for example, tried to increase the sensitivity by increasing the number of thermo-junctions.[31] Different thermo-couples have been employed.

[28] d'Arsonval. Soc. Franc. de Phys., 1886, pp. 30, 77.

[29] Boys, C. V. Proc. Roy. Soc. 1887, *42*, p. 189; 1888, *44*, p. 96; 1890, *47*, p. 480; Philos. Trans., 1889, *180A*, p. 159.

[30] Paschen, F. Ann. der Phys., 1893, (3) *48*, p. 272.

[31] An advantage is gained in the thermopile by increasing the number of thermo-couples, but not in the radio-micrometer. In a thermopile the highest efficiency is attained when the resistance of the thermo-couples is equal to the combined resistance of the connecting wires and the auxiliary galvanometer. Since the resistance of a single thermo-couple is much less than this combined resistance, it is of advantage to use several pairs of junctions. In the case of the radio-micrometer, however, the connecting loop of wire has a negligible resistance, hence there is nothing to gain by using more than a single pair of junctions; for as the electromotive force is increased by the addition of junctions, there is a proportionate increase of resistance and the throw of current remains constant.

Féry,[32] for example, used silver and constantan; Schmidt[33] bismuth and antimony; and Coblentz,[34] also bismuth and antimony, and later bismuth and silver.[35] Hollnagel[36] added greatly to the sensitivity and constancy of the instrument described by Schmidt by operating it in a vacuum; Coblentz[37] increased the sensitivity of his bismuth-silver radio-micrometer by enclosing it in a vacuum; and Rubens and Hollnagel,[38] and Rubens and Wood[39] succeeded in obtaining an increase of sensitivity for the instrument described by Schmidt by using a concentrating or conical receiver. Coblentz also found that the sensitivity of his instrument was lowered by para- and dia-magnetic effects produced by the field magnets. He was able to lessen these effects and add thereby to the delicacy of response by using weak field magnets; or if strong, by placing them as far above the thermo-junctions as was possible. The elimination of these effects he considers one of the chief obstacles to be overcome in the future construction of the instrument.[40]

As a working instrument the radio-micrometer may be said to have the following advantages: (a) It is self-contained; (b) it is non-selective in its response to wave-length; (c) it is little subject to magnetic perturbations; and (d) it has a high constancy of the zero-reading.

[32] Fery, C. Comptes Rendus, 1909, *148*, p. 915.

[33] Schmidt, H. Inaug. Diss., Berlin, 1909; Ann. der Phys., 1909, *29* (5), p. 1004. See also U. Meyer. Ann. der Phys., 1909, *30* (5), p. 612.

[34] Coblentz, W. W. Bulletin Bureau of Standards, 1906, *2*, p. 479.

[35] On p. 10 (Bulletin Bureau of Standards, 1913, 9), Coblentz says: "From later experience it seems desirable to try constantan instead of bismuth."

[36] Hollnagel, H. Inaug. Diss., Berlin, 1910.

[37] Coblentz, W. W. Bull. Bureau of Standards, 1906, *2*, p. 479; 1908, *4*, p. 396.

[38] Rubens, H. and Hollnagel, H. Sitz Ber. d. könig. Preuss. Akad. Wiss., Berlin, 1910, No. *2*, p. 26.

[39] Rubens, H. and Wood, R. W. *Ibid.*, 1910, No. 52, p. 1122.

[40] For further reports of work with the radio-micrometer see Lewis, E. P. Astrophysical Journal, 1895, *2*, p. 1; Wilson, W. E. Proc. Rov. Soc., 1894, *55*, p. 246; 1895, *58*, p. 174; 1896, *60*, p. 377; and Julius, W. T. Handlungen, 5, de Nederlandisch Natuur en Geneeskundig Congress, 1895.

D. The Bolometer.

As has already been stated the bolometer is an instrument depending for its response to radiant energy on the change in resistance with change in temperature offered by a metal to the flow of an electric current. The instrument is essentially a Wheatstone bridge, two arms of which are made of very thin blackened metal strips (of high electrical resistance and high temperature coefficient), one or both of which are exposed to radiation. When thus exposed there is a change of temperature which unbalances the bridge, and the resulting deflection of the needle of the galvanometer in circuit with the bridge gives a measure of the energy absorbed. In order that the instrument shall be sensitive to small radiation quantities, it is obvious that the metal used should have a high temperature coefficient of resistance, a small specific heat, and a low heat conductivity. Such metals are nickel, platinum, tin, and iron. For various reasons relating to mechanical construction, however, platinum is much more frequently used than the others.

The earliest account of an instrument depending on change of electrical resistance for measuring or detecting radiant energy appears to be that of Svanberg, 1851,[41] who for this purpose introduced a flat spiral of blackened copper wire into one of the arms of a Wheatstone bridge. Langley, 1881,[42] was the first however, to invent a practical instrument and demonstrate its superiority to all radiation meters existing at that time for accuracy, quickness of action, and adaptability. As is shown in the reference appended below, his improvements of the instrument extended over a long period of time. The value of these improvements may be shown by comparing the sensitivity of his earlier and later instruments. The first had a sensitivity of 0.00002° per mm. deflection of the galvanometer, and the latest recorded a temperature change of 0.000001° per mm. deflection when used with a galvanometer having a figure of merit of $i=5 \times 10^{-10}$ ampere.

[41] Svanberg, A. F. Pogg. Ann. der Phys., 1851, *84*, p. 416.

[42] Langley, S. P. Proc. Amer. Acad., 1881, *16*, p. 342; Chemical News, 1881, *43*, p. 6; Brit. Assoc. Report, 1894, p. 465; Annals Astrophys., Obs. I.

1. *Important points in the construction of sensitive bolometers.* Obviously effective sensitivity can be added in two ways in the use of the bolometer: (1) by improving the bolometer itself; and (2) by making more delicate the auxiliary galvanometer. In the attempt to construct sensitive bolometers with as great constancy of the zero as is possible, the following are some of the points that have received attention.

a. *The kind of material to be used for the receiving surface.* As has been stated the problem is to get a metal having a high temperature coefficient of resistance, low specific heat; and low conductivity of heat.[43] The following metals have at various times been used: platinum,[44] tin,[45] nickel,[46] and iron.[47]

b. *The area of the receiving surface.* The sensitiveness has been found to be closely proportional to the square root of this surface. In spectral energy work, therefore, where the bolometer strip is narrow the sensitiveness attainable for the bolometer is limited.

c. *The thickness of the strip used as receiver.* There is a mechanical limit to the thinness of the strip that can be used when exposed to the air. Langley[48] found that platinum strips, for

[43] According to Lummer and Kurlbaum (Wied. Ann. der Phys., 1892, *46*, p. 208) the following equation expresses the relation between the sensitiveness of the bolometer, S; the bolometer current, I; the temperature coefficient of the area exposed to radiation, e; the area of the strip exposed to radiation, a; the resistance of the bolometer strips, r; the absorption coefficient of the surface exposed to radiation, A; the emissivity of the whole surface, E; the area of the whole surface, F; the heat capacity, W; and the galvanometer constant, k.

$$S = \frac{I}{8}\, e\, a\, k \sqrt{r\, \frac{f_1(A)\, f_3(F)}{f_2(E)\, f_4(W)}}$$

From this equation it will be seen that the sensitiveness is increased by decreasing the heat capacity and the emissivity; and by increasing the bolometer current, the temperature coefficient, the resistance, the absorption coefficient, and the surface.

[44] Langley, S. P. *Loc. cit.*

[45] Angström, K. Wied. Ann. der Phys., 1885, *26*, p. 253; 1889, *36*, p. 715; 1893, *68*, p. 493, and others.

[46] Julius, W. T. Licht und Wärmestrahlung, 1890, p. 31.

[47] Rubens, H., (used tin, iron, and platinum). Wied. Ann. der Phys., 1889, *37*, p. 255; and 1892, *45*, p. 238.

[48] Langley, S. P. *Op. cit.*

example, less than 0.002 mm. thick are inadvisable, thinner ones being disturbed mechanically by air currents. In recent work Coblentz[49] finds it permissible to use platinum strips 0.001 mm. in thickness. In vacuum bolometers, however, much thinner strips (0.0005 mm.) are used to advantage.

d. *The most favorable resistance of bolometer and balancing coils.* Lummer and Kurlbaum[50] considered the bolometer a simple Wheatstone bridge which has its maximum sensitiveness when the four arms and the galvanometer are all of equal resistance. In fact in the construction of their instrument instead of using one or two bolometer surfaces, they used four just alike, each forming one of the arms of the bridge.[51] Child and Stewart,[52] however, have shown experimentally that the sensitiveness is increased by having the resistance of the balancing coils several times that of the bolometer strips. Abbot[53] has also shown that the maximum sensibility is very nearly attained when the resistance of the balancing coils is four times or more that of the bolometer strips, and the galvanometer resistance is not less than 0.6 or more than four times the resistance of the bolometer strips.[54]

e. *The slide wire for balancing the resistance.* The question of a satisfactory slide wire has required considerable attention. Coblentz has found that slide wires of platinum 0.5 and 1 mm. in diameter used in connection with a mercury contact give the best satisfaction.

f. *The protection of the bolometer from air currents.* This can be done adequately only by putting the bolometer in a vacuum. Contact with the air renders the bolometer both insensitive and inconstant in its response. On the former point,

[49] Coblentz, W. W. Bulletin of the Bureau of Standards, 1912, *9*, p. 37.

[50] Lummer, O. and Kurlbaum, F. Wied. Ann. der Phys., 1892, *46*, p. 204.

[51] The tendency among foreign investigators has been to make the four arms of equal resistance. On the other hand just as strong a tendency has been shown among American investigators to make the resistance of the balancing coils greater than that of the bolometer strips.

[52] Child, C., and Stewart, O. Phys. Rev., 1897, *4*, p. 502.

[53] Abbot, C. G. Annals of the Astrophysics Obs., I.

[54] See also Reid, H. F. Amer. Jour. Sci., 1888, *33*, (3), p. 160.

Warburg, Leithäuser, and Johansen[55] have shown that the heat lost by air conduction for a bolometer 1 mm. wide is 4.5, and for a bolometer 0.2 mm. wide, 14.8 times as great as it is from radiation. And in a vacuum a bolometer 0.2 mm. wide when operated with a small current was found to be ten times as sensitive as it was in air.[56]

g. *The strength of current.* The radiation sensitivity of a vacuum bolometer is found to be proportional to the current for small values but for a large current the radiation sensitivity of a narrow bolometer passes through a maximum. This maximum is obtained for a current density at which the radiation sensitivity of the air bolometer does not depart appreciably from proportionality with the current. The manner in which the radiation sensitivity varies with the gas pressure and with the bolometer current is shown, for example, by Buchwald.[57]

2. *Points in the construction of the auxiliary galvanometer.* It is scarcely necessary to mention that the effective sensitivity of the bolometer depends in a large measure upon the auxiliary galvanometer. The first great step in improving the moving magnet galvanometer is due to Kelvin who decreased the weight of the moving parts to a few milligrams, and introduced the static system of magnets. Snow[58] was among the first to give much attention to the possibility of adding sensitivity to the bolometer by improving the galvanometer. Paschen[59] continued the work in this direction and constructed the most sensitive galvanometer used up to that time. DuBois and Rubens,[60] Mendenhall and

[55] Warburg, E., Leithäuser, G. and Johansen, E. Ann. der Phys., 1907, *24*, (5), p. 25.

[56] A noteworthy vacuum spectro-bolometer is described by A. Trowbridge (Phys. Rev., 1908, *27*, p. 282; Philos. Mag., 1910, (6), *20*, p. 768) in which the bolometer and the optical parts of the spectroscope are in a vacuum. Coblentz also describes a very sensitive vacuum bolometer and gives results with it at different pressures (Bull. Bureau of Standards, 1913, *9*, pp. 39-43). Other less adequate methods of shielding have been to surround the bolometer by a double wall with an air space between; to enclose it in a water jacket (Langley, *op. cit.* and Abbot, *op. cit.*); etc.

[57] Buchwald, E. Ann. der Phys., 1910, (4), *35*, p. 928.

[58] Snow, B. W. Phys. Rev., 1895, *1*, p. 31.

[59] Paschen, F. Wied. Ann. der Phys., 1893, *48*, p. 272.

[60] DuBois and Rubens. Ann. d. Phys., 1900, (4), *2*, p. 84.

Waidner,[61] Abbot,[62] Ingersoll,[63] and Coblentz[64] have all described sensitive galvanometers. Some of the points to be considered in the construction of a sensitive galvanometer are form and size of coil, size of wire, the kind of magnet and the dimensions and construction of the needle system, the astaticizing of the magnet system, the shielding of the system from influences due to the earth's field and neighboring objects, etc. The proper form and method of winding galvanometer coils to secure a maximum effect from a given weight or resistance of copper has been thoroughly discussed by Maxwell.[65] He shows that the greatest effect is obtained by winding the coils with different sizes of wire, beginning with the smallest size and winding each layer so that it lies within the surface the polar equation of which is $r^2 = d^2 \sin\theta$, where r is the length of the radius making an angle θ with the axis of the coil, and d the value of r when $\theta = 90°$. Abbot[66] has computed the most efficient coils for meeting these conditions, and gives results for coils wound with a single wire and for coils wound with three sections of wire of different diameters. He found that the total force exerted at the center is closely proportional to the 0.45 power of the total resistance and that coils composed of three sections of the best sizes of wire give 1.4 times the force of a coil of the best single size wire of the same total resistance. In his best 25 ohm coil, wound in three sections the diameters of the wires were 0.08, 0.16, and 0.32 mm.; the lengths were 256, 1031, and 4144 cm.; and the external diameter of the completed coil was 3.3 cm.

In the construction of the needle system the greatest sensitivity is attained when the ratio of the magnetic moment to the moment of inertia of the system is a maximum. The best dimensions and construction of needle systems have been extensively investigated

[61] Mendenhall, C. E. and Waidner, C. W. Amer. Journ. Sci., 1901, 12, (4), p. 249.

[62] Abbot, C. G. Astrophys. Journ., 1903, *18*, p. 1.

[63] Ingersoll, L. R. Philos. Mag., 1906, (6), *11*, p. 41.

[64] Coblentz, W. W. Bulletin Bureau of Standards, 1908, (3), *4*, pp. 424-435; 1916, *13*, p. 423.

[65] Maxwell, J. C. Electricity and Magnetism, *2*, p. 322.

[66] Abbot, C. G. *Loc. cit.*

by Paschen, Mendenhall and Waidner, and by Abbot. The shielding of the galvanometer from magnetic perturbations, etc., is done by means of housings of soft iron. For an inexpensive and convenient method of shielding, for a simplification of the moving coil galvanometer for convenience of shielding, and for the astaticization of the needle system, see Coblentz (*loc. cit.*).

3. *Possible sources of difficulty in the use of the bolometer.* The preceding discussion though brief may be enough to indicate that the bolometer is a difficult instrument to operate. The following are the possible sources of trouble. (1) The auxiliary galvanometer is subject to magnetic perturbations and if exposed to great temperature changes its sentiveness is changed, due to a variation in the resistance of the coils. The sensitiveness and zero reading are also subject to frequent changes due to variations in the magnetic field. (2) The bolometer strip is affected by air drafts, and, if very thin, by mechanical vibration. (3) The electric circuits are subject to temperature (resistance) changes which cause variations in the bolometer current. (4) The storage battery current is irregular due to changes in temperature and to polarization. (5) The gases surrounding the bolometer may affect the readings. Lummer and Pringsheim[67] found, for example, that variations in the amount of moisture in the air change the sensitiveness of the bolometer. A part or all of these causes tend to make the readings in work with the bolometer extremely variable. These variations are of two kinds. (a) A slow drift of the zero scale reading due to changes in the resistance of the bridge; and (b) fluctuations of the reading due to air currents and magnetic perturbations.

4. *The comparative advantages and disadvantages of the bolometer.* The bolometer has, however, the following advantages. It has a high degree of sensitivity. It is portable. It is non-selective in its response to wave-length. It can be calibrated directly against a black body. It is quick in its action and is, therefore, well adapted to work in which a quick registration of the galvanometer deflections is desired. Its chief disadvan-

[67] Lummer, O. and Pringsheim, E. Ann. der. Phys., 1897, (3), *63*, p. 398.

tage, as has been stated, is its unsteadiness and the difficulty of operating. It is not nearly so easy to operate as the thermopile, for example; and the unsteadiness of its zero point renders it untrustworthy for small readings in spite of its high intrinsic sensitivity.

E. The Selenium Cell

To Willoughby Smith belongs the discovery that has led to the use of selenium as a light-measuring instrument. In 1873 while using a resistance made of selenium in connection with experiments in telegraphy, he discovered that its electrical conductivity is raised by exposure to light. The immediate result of this discovery was twofold: light-measuring instruments were constructed of selenium, and a long series of investigations was begun to determine (a) the factors extraneous to light that influence the resistance of selenium and thus affect its applicability to the measurement of light; (b) the factors that influence the action of light on the conductivity of a selenium cell and the possibility of the use of the cell either as a photometer or a radiometer; and (c) the nature of the action of light on the specific resistance of selenium.

A selenium cell is a device consisting essentially of a mass of crystalline selenium furnished with two metallic electrodes. Crystalline selenium is obtained by keeping molten vitreous selenium at a temperature of from 150 to 210° C. for several hours. It then takes on a metallic appearance and becomes opaque even in case of very thin films. Selenium has such a very small conductivity that in making resistances of it, one feature of the construction is to offer several paths or rather one continuous broad path for the flow of current. One way in which this has been accomplished in the construction of light-measuring cells has been to wind a strip of mica or slate with two parallel wires less than 1 mm. apart. This is covered with powdered selenium. The selenium is melted, worked into a smooth surface and cooled quickly. It is then heated again and cooled very slowly. One end of each wire is connected to the battery terminals, the others end in the selenium. The wires thus in reality form the electrodes, and the circuit is completed through the intervening selenium. This type

of cell has been used among others by Bidwell, Siemans, Sabine, and Pfund. (For construction of selenium cells, see Bidwell,[68] Fritts,[69] Berndt,[70] Townsend[71] and Dieterich.[72])

1. *Points to be considered in the construction and use of selenium cells.* The following are some of the points to be considered in the construction and use of sensitive selenium cells.

a. *The method of preparation.* The sensitiveness of the cell to light depends largely upon its initial specific resistance. This has been pointed out by Pochettino[73], Giltay,[74] and especially by Brown.[75] According to Brown, the higher the resistance of crystalline selenium the greater is its sensitivity to light; and conversely the lower its resistance, the less is the sensitivity. Brown gives results showing the resistance of the cell and its sensitivity in terms of the ratio of conductivity in light to conductivity in the dark. For example, a cell with a resistance of 10^9 ohms had a sensitivity of 200:1 in an arbitrary scale; a cell with a resistance of 400,000 ohms, a sensitivity of 30:1; 3,000 ohms, 2:1; 1,700 ohms, 1:1. In its vitreous state selenium is practically a non-conductor. To become a conductor it must be brought to the crystalline form. For example, when it is heated to a temperature of 100 to 150° C. its conductivity is slight and variable; but when heated repeatedly to temperatures of 190 to 210° C. and cooled, it passes into a coarsely granular crystalline state and acquires and retains a greater conductivity. That the temperature to which selenium has been heated is the chief factor in determining its conductivity and sensitivity to light was pointed out by Siemans[76] as early as 1875, who stated that when heated to 210° C. cells of greater conductivity, constancy, and light sensitivity were produced than when heated to 150° C. A systematic study of the

[68] Bidwell, S. Phil. Mag., 1891, Ser. 5, *31*, pp. 250-256; 1895, *40*, pp. 233-256.
[69] Fritts. Electrical Review, 1885, p. 208.
[70] Berndt, G. Phys. Zeit., 1904, *5*, pp. 121-124.
[71] Townsend, F. Electrician, Oct. 7, 1904, *53*, pp. 987-990.
[72] Dieterich, E. O. Phys. Rev., 1914, *4*, Ser. 2, pp. 467-476.
[73] Pochettino, A. N. Cimento, 1911, *1*, Ser. 6, pp. 147-210.
[74] Giltay, J. W. Phys. Zeit., 1910, *11*, p. 419.
[75] Brown, F. C. Phys. Rev., 1911, *33*, pp. 1-26.
[76] Siemans, W. Phil. Mag., 1875, *50*, p. 416.

effect of temperature and the duration of annealing on the resistance of selenium has been made by Dieterich.[77] His results show that when maintained at a temperature of 200 to 210° C. for six hours, a cell was produced with a resistance of 233,000 ohms; at 210° for four hours, a resistance of 358,000 ohms; at 210° for five hours, 490,000 ohms; at 180° for three and one-half hours, 1,400,000 ohms; and at 190° for two hours, 3,690,000 ohms. Inasmuch as his cells of highest resistance were not permanent, he was not able unfortunately to work out the correlation between resistance and sensitivity. Pochettino,[78] Aichi and Tanakadate,[79] Brown,[80] and Dieterich[81] all think that a change of structure takes place when selenium is annealed at a temperature of 210 to 220° which causes the increase of conductivity.

b. *Purity of the selenium.* Bidwell[82] found that insensitive selenium cells were increased in sensitivity by the addition of a small quantity of cuprous selenide. Marc[83] recommends the addition of 0.1-0.5% of silver to increase its sensitivity. Townsend[84] claims that 1 or 2% of copper or nickel selenide may be present without affecting to a marked degree the sensitivity of the cell. Pfund[85] found that the sensitivity could be increased by the presence of 3% of a selenide. He believes it to be of advantage, however, to start with a chemically pure selenium and add impurity of a definite kind and amount.

c. *Material and size of electrodes.* Sale,[86] and Adams and Day[87] used platinum electrodes; Bell[88] used brass; Bidwell,[89]

[77] Dieterich, E. O. *Loc. cit.*
[78] Pochettino, A. N. Cimento, 1911, *1*, Ser. 6, pp. 147-210.
[79] Aichi, K. and Tanakadate, T. Math. and Phys. Soc., Tokyo, 1904, (2), *16*, pp. 217-221.
[80] Brown, F. C. *Loc. cit.*
[81] Dieterich, E. *Loc. cit.*
[82] Bidwell, S. Phil. Mag., 1895, *40*, Ser. 5, pp. 233-256.
[83] Marc, R. Z. Anorg. Chem., 1906, *48*, pp. 393-426.
[84] Townsend, F. *Loc. cit.*
[85] Pfund, A. H. Phil. Mag., 1904, *7*, Ser. 6, pp. 26-39.
[86] Sale. Proc. Roy. Soc. of London, 1873, *21*, pp. 283-285.
[87] Adams and Day. Philos. Trans., 1877, *167*, pp. 313-349.
[88] Bell, G. Nature, 1878, *22*, p. 500.
[89] Bidwell, S. *Loc. cit.*

copper; Pfund[90] and Berndt,[91] carbon. Dieterich[92] tried copper, nickel, platinum, German silver and Advance wire. He found that copper, German silver and Advance wire have the disadvantage that at the temperature of annealing a film of oxide is formed. This so materially increases the resistance of the cell as to make it practically useless except with very sensitive auxiliary apparatus. Nickel wire is much less easily oxidized and proved as satisfactory as platinum wire besides being less expensive. Pfund and Berndt consider carbon electrodes preferable in that selenium forms no conducting compound with carbon. On the question of size of electrodes, there seems to be general agreement that large surface contact between the junctions and the selenium is necessary to avoid high junction resistance and consequent diminished sensitivity of the cell.

d. *Strength of the battery current.* The sensitivity of the selenium cell has been found to vary with the battery current. It was first noted by Adams and Day[93] that the resistance of selenium diminished as the battery current is increased. Sabine[94] held this to be true only after a certain intensity of current had been reached. For lower intensities of current, increase of current caused increase of resistance. Minchin[95] increased the conductivity of his cell fourfold by increasing the voltage from 2 to 12 volts. Brown[96] found that with a Ruhmer cell the conductivity varied by an amount almost directly proportional to the voltage; with a Giltay cell, however, the variation decreased in amount as the voltage was increased. Ries[97] claims that conductivity increases with increase of voltage for a range of from 0.4 to 4 volts. Luterbacher[98] states that this change is greater for direct than for alternating current. The necessity for an accurately

[90] Pfund, A. H. *Loc. cit.*
[91] Berndt, G. *Loc. cit.*
[92] Dieterich, E. O. Phys. Rev., 1914, *4*, Ser. 2, p. 468.
[93] Adams and Day. *Op. cit.*, p. 319.
[94] Sabine, R. Phil. Mag., 1878, *5*, ser. 4, pp. 401-416.
[95] Minchin, G. M. Phil. Mag., 1891, *31*, ser. 5, pp. 207-238.
[96] Brown, F. C. *Loc. cit.*
[97] Ries, C. Phys. Zeit., 1911, *12*, p. 529.
[98] Luterbacher, J. Ann. der Physik, 1910, *33*, p. 1392.

constant battery current when using a selenium cell as a measuring instrument is obvious.

e. *The direction of the battery current.* Adams and Day[99] found that the passage of a current in any direction at any period in a series of observations produces a condition which tends to facilitate the subsequent passage of a current in the opposite direction but obstructs one passing in the same direction. He interprets this condition as a slight "set" of the molecules. The effect is particularly marked in case of the first current sent through the selenium and is more or less permanent. This result was confirmed by Sabine[100] who thinks the changes are in the resistance of both the selenium and the junctions. This fact combined with the changes in resistance caused by changes in the strength and duration of current led Sabine to state that selenium is very unsuitable for the production of a constant resistance for measuring purposes.

f. *Duration of battery current.* Adams and Day[101] found that the resistance of selenium increases continuously during the time of the passage of the battery current. They point out, for example, that on this account the precaution should always be taken to shut off the current between observations. This precaution, however, does not eliminate; it only lessens the effect of the variable factor.

g. *Temperature.* Bidwell[102] claims that there is an optimum temperature for each cell above and below which the resistance decreases. For six cells this temperature was 24, 23, 14, 30, 25 and 22° C. Brown and Stabbins[103] tested the effect of temperatures ranging from 40° to 200° C. and found that the resistance of selenium decreases with increase of temperature. Temperatures above or below these were not used, so their results contain nothing that bears directly on the claim made by Bidwell. For a change of temperature ranging from 13.2° to 73.4° C. they found that a given amount of light incident on the cell caused changes of

[99] Adams and Day. *Op. cit.*, p. 323.
[100] Sabine, R. *Loc. cit.*
[101] Adams and Day. *Op. cit.*, p. 314.
[102] Bidwell, S. Phil. Mag., 1881, *11*, Ser. 5, p. 302; 1895, *40*, ser. 5, p. 242.
[103] Brown and Stebbins. Phys. Rev., 1908, *26*, pp. 273-298.

resistance varying in percentage from 24.9 to 3.7. The effect of temperature on the sensitivity of the cell is so marked that Pfund, for example, worked in a room in which the temperature was kept constant to 1/10°.

h. *Pressure.* According to Brown,[104] Brown and Stebbins,[105] and Montén,[106] increase of pressure decreases the resistance of selenium and lowers its sensitivity to light. Brown found that these effects were present up to a pressure of 1,000 atmospheres. In case of a single crystal of selenium, he increased the conductivity about 120 times by an increase of pressure of 180 atmospheres. Brown and Stebbins found the percentage change of resistance for one atmosphere to vary between 0.05 and 0.30 for different cells.

i. *Moisture.* Ries,[107] Bidwell[108] and others have shown that humidity affects the electrical properties of selenium. Ries thinks this effect is sufficient to explain the discrepancies existing in the results of different observers. On this account cells of the Giltay type, which are constructed so that there is free communication between the outer air and the selenium surface, show wide variations in conductivity. Nicholson[109] improved the constancy of a cell of this type by enclosing it in an air-tight box with a glass window.

j. *Age of cell.* Adams and Day[110] found the sensitivity of the selenium cell to be greatly reduced after one year. Bidwell[111] found no material loss at the end of one year, but the cells were practically useless after four years. Dieterich,[112] however, constructed two cells of remarkably high sensitivity which lost 4/5 of their sensitivity within a month.

[104] Brown, F. C. Phys. Rev., 1905, *20*, pp. 185-186; Phys. Rev., 1914, *4*, ser. 2, pp. 85-98.

[105] Brown and Stebbins. *Loc. cit.*

[106] Montén, F. Ark. för. Mat. Astron. och. Fysik, Stockholm, 1908, *4*, pp. 1-6.

[107] Ries, C. Phys. Z., 1908, *9*, pp. 569-582.

[108] Bidwell, S. Phil. Mag., 1895, *40*, ser. 5, p. 245.

[109] Nicholson, P. J. Phys. Rev., 1914, *3*, Ser. 2, p. 8.

[110] Adams and Day. *Op. cit.*, p. 348.

[111] Bidwell, S. Phil. Mag., 1891, *31*, Ser. 5, pp. 250-256.

[112] Dieterich, E. O. Phys. Rev., 1914, *4*, Ser. 2, p. 471.

k. *The amount of polarization gradually set up in the cell.* The presence of polarization currents produced by the passage of a battery current though selenium was found by Adams and Day.[113] This effect was increased by the exposure of the selenium to light. Bidwell[114] says the polarization current is very troublesome in making accurate resistance tests by the bridge method. The intensity of this current is increased by humidity. While this factor and the next to be considered, the presence of photo-electric currents, can hardly be said to influence the sensitivity of the cell in a way similar to the preceding factors, they undoubtedly affect its use as a light-measuring instrument; for with the presence of polarization and photo-electric currents of unknown intensity, an exact determination of the conductivity of the cell under a given set of conditions can not be made.

l. *Photo-electric currents.* The presence of photo-electric currents in selenium due to an exposure to light was noted first by Adams and Day,[115] later by Bidwell [116] and by Minchin.[117] Adams and Day found that this current was often more intense than the polarization current and was sufficient to overbalance a weak battery current.

2. *Factors which render it difficult to use the selenium cell for quantitative work either as an ohmic resistance or as a light-measuring instrument.*

A part of the foregoing factors are of importance chiefly in making it almost impossible to construct two selenium cells of similar properties. They do not affect the use of a given cell once constructed. The remainder, however, apply to the responses of a single cell and are so difficult if not impossible of control as to make it exceedingly doubtful whether the selenium cell can be used as an instrument of precision. In fact the consensus of opinion among the investigators has been that it can not be used with a degree of precision which is acceptable in quantitative

[113] Adams and Day. *Op. cit.*, p. 328.
[114] Bidwell, S. Phil. Mag., 1895, *40*, Ser. 5, p. 244.
[115] Adams and Day. *Op. cit.*, p. 333.
[116] Bidwell, S. *Op. cit.*, p. 251.
[117] Minchin, G. M. Phil. Mag., 1891, *31*, Ser. 5, pp. 207-238.

work. These factors are: (1) The passage of the battery current through the cell in a given direction produces a condition which tends to facilitate the subsequent passage in the opposite direction, but obstructs one in the same direction. Since this effect can not be completely eliminated and the cell restored to its original condition by reversing the current, the cell continually changes its state of conductivity with use; hence two measurements can never be made with it in the same condition. This difficulty is further increased by the fact that the longer the current is allowed to flow, the greater is the change of conductivity. The greater number of times the cell is used, therefore, and the longer the current is allowed to flow, the greater will be the progressive change in the properties of the cell. (2) Over and above the effect of current is a loss of sensitivity with age. Measurements made by the cell at intervals at all widely separated are, therefore, not comparable. (3) The polarization currents due to the passage of the battery current and increased by the exposure to light, and the photo-electric currents which are even stronger than the polarization currents and strong enough according to Adams and Day to overcome a weak battery current, produce a variability in the action of the cell for which there seems to be no remedy. When to these apparently insuperable obstacles is added the fact that the strength of the battery current, the temperature of the cell and the humidity of the atmosphere must be kept constant within small limits, one gets some idea of the difficulties attendant on the use of the selenium cell as an instrument of precision.

3. *Factors which apply especially to its use as a light measuring instrument.* The foregoing properties of selenium, it may be noted, apply to its use as material for the construction both of ohmic resistances and of instruments for the measurement of light. In addition to these the following points which apply specifically to its use in the measurement of light are to be considered.

a. *The preexposure of the cell.* Adams and Day[118] claim that

[118] Adams and Day. *Op. cit.*, p. 315.

selenium is more sensitive in its response to light after it has been kept in the dark for several hours than after it has been exposed to light several times; hence the result obtained from the first of a series of measurements is generally not comparable with those gotten later. Townsend[119] says that after prolonged exposure to light there is a fatigue effect which takes place immediately and lasts at least four hours. Nicholson[120] says that fatigue effects are present when the cell has not been allowed sufficient rest between readings. Marc[121] finds that the sensitivity to red light is greatly modified by a previous strong illumination with white light or by a long continued blue illumination. Grantham[122] investigating the recovery period of the cell, found that for a short time after the exposure to light was cut off, the resistance decreased still further; it then increased rapidly at first, then more slowly. After constant use the cells became at times temporarily almost insensitive.

b. *The time of exposure to light.* For Pfund[123] a maximum response was reached in 2 to 3 sec.; then a slight "creeping effect" took place. In later work he[124] used an exposure time of 12.5 seconds. Brown[125] claims that the change of conductivity is a function of the time of illumination. For effect of exposure time on response to monochromatic light, see pp. 35-36.

c. *The wave-length of the spectrum light and the factors which influence the selectiveness of response to wave-length.* Sale[126] was the first to report that selenium is selective in its response to wave-length. He found the greatest change in resistance was caused by red light near the end of the solar spectrum; next by red of shorter wave-length; then in order by orange, green, blue and violet. Adams and Day[127] found the

[119] Townsend, F. *Loc. cit.*
[120] Nicholson, P. J. *Op. cit.*, p. 9.
[121] Marc, R. Z. Anorg. Chem., 1903, *37*, pp. 459-475.
[122] Grantham, G. E. Phys. Rev., 1914, *4*, Ser. 2, pp. 259-266.
[123] Pfund, A. H. Phil. Mag., 1904, *7*, Ser. 6, pp. 26-39.
[124] Pfund, A. H. Phys. Rev., 1912, *34*, p. 370.
[125] Brown, F. C. Phys. Rev., 1911, *33*, pp. 14-15.
[126] Sale. Proc. Roy. Soc. of London, 1873, *21*, pp. 283-285.
[127] Adams and Day. *Op. cit.*, p. 317.

greatest light effect in the greenish yellow, next in the red and least in the violet. Pfund[128] used lights equalized in energy by a thermopile and later by a radiomicrometer. He got the maximum response near .7μ. This maximum was not changed when selenides of lead, mercury, copper, and silver were introduced. Brown and Sieg[129] found the curve of response to wave-length to vary for different types of cell. With reference to selectiveness of response to wave-length two sorts of investigation have been made, —one to determine the factors that influence this selectiveness in a given cell; the other to determine the factors which influence selectiveness in different cells.

(1) *Factors which have been found to influence the selectiveness of response for a given cell.* The following factors have been found to influence the selectiveness of response in a given cell.

(a) *Intensity.* Pfund[130] found the sensitivity curve for wavelength to vary with the intensity of the incident light. This was confirmed by Brown and Sieg[131] and by Nicholson.[132] With reference to the changes in the sensitivity curve Pfund contributes the following formula: $d=DI^{\beta}$ where d= change of conductivity; I= energy of illumination; and D and β are constants dependent on the wave-length of the incident light. For exposures of 12.5 sec., he found D to be constant for any particular wavelength; β was very nearly ½ for regions of the spectrum from the violet to the yellow; but its value increased as red was approached, equalling 1 for deep red and infra-red. Nicholson verified both the formula and the constants for an exposure time of 12.5 sec.

(b) *Length of exposure time.* Nicholson,[133] however, found the formula contributed by Pfund to hold only for an exposure time of 12.5 sec. For longer and shorter exposures, the value of β changed. For 10 sec. exposure, it increased and the region in

[128] Pfund, A. H. Phil. Mag., 1904, *7*, Ser. 6, pp. 26-39; Phys. Rev., 1909, *28*, pp. 324-336.

[129] Brown, F. C. and Sieg, L. P. Phys. Rev., 1914, *4*, Ser. 2, pp. 48-61.

[130] Pfund, A. H. Phys. Rev., 1909, *28*, pp. 324-336.

[131] Brown, F. C. and Sieg, L. P. Phys. Rev., 1913, *2*, Ser. 2, pp. 487-494.

[132] Nicholson, P. J. Phys. Rev., 1914, *3*, Ser. 2, pp. 1-24.

[133] Nicholson, P. J. *Loc. cit.*

which β becomes 1 shifted towards the shorter wave-lengths. With longer exposures (15 to 20 sec.), the value of β decreased. With unlimited exposures or until a steady state of resistance of the selenium was attained, β equalled 0.5 throughout the spectrum, except at about 600$\mu\mu$ where it equalled only 0.4. This change in the value of β for different wave-lengths with exposure time is probably in accord with Nicholson's further demonstration that selenium has a different inertia of response for different wave-lengths. This is particularly marked for the red and infra-red of the spectrum. Brown and Sieg[134] also note a change in the shape of the sensitivity curve for exposures of 30 and 0.4 sec.

(c) *Temperature, humidity and voltage.* That the selectiveness of response of selenium to wave-length varies with the temperature of the cell is mentioned by Marc[135] and Nicholson;[136] Marc finds it to vary also with the intensity of the current used; and Nicholson with the humidity.

(d) *Photo-electric currents.* Minchin[137] using seleno-aluminium cells, found that the intensity of electromotive force produced by the action of light on the cell varies with the wave-length of the incident light. It is greatest in order for yellow, orange, green, red and blue.

(2) *Factors which have been found to influence the selectiveness of response to wave-length in different cells.* The main cause of difference in the selectiveness of response to wave-length from cell to cell is according to Brown and Sieg[138] and to Dieterich[139] the temperature at which the cell was made and annealed. In general there are two groups of cells,—those with the maximum response at wave-lengths greater than 640$\mu\mu$; and those with the maximum at a wave-length less than this. Cells of the former group are produced by annealing at lower temperatures, *e.g.*, annealing at 170° C. gives a pronounced red maximum;

134 Brown and Sieg. Phys. Rev., 1913, *2*, Ser. 2, pp. 487-494.
135 Marc, R. Z. Anorg. Chem., 1903, *37*, pp. 459-475.
136 Nicholson, P. J. *Loc. cit.*
137 Minchin, G. M. Phil. Mag., 1891, *31*, Ser. 5, pp. 207-238.
138 Brown, F. C. and Sieg, L. P. Phys. Rev., 1914, *24*, Ser. 2, pp. 48-61.
139 Dieterich, E. O. Phys. Rev., 1914, *4*, Ser. 2, pp. 467-476.

those of the latter group by annealing at high temperature, *e.g.*, at 210° C. By partial annealing at 210° and completing the process at a lower temperature, the maximum response is given in the blue and a secondary maximum in the red. Brown[140] confirms this result with his selenium "crystal forms" produced by the sublimation of the vapor either in a high vacuum or at atmospheric pressure. Among these forms he finds types which give the different wave-length sensitivity curves found by Dieterich in the different cells annealed at the various temperatures. Brown believes that there are at least three forms of metallic selenium of widely different electrical resistivity. These forms are produced at different temperatures. That is, at high temperatures, for example, crystals of maximum sensitivity to red light are not allowed to form.

d. *The intensity of white light.* Attempts have been made to use the selenium cell both as a radiometer and a photometer. In the latter case, the following laws of change of resistance with change of intensity have at different times been formulated. When m= conductivity, i= light intensity, R= resistance, and the other quantities are constants, Rosse,[141] Adams and Day,[142] and Berndt[143] give the formula i= cm^2; Hopius,[144] i= cm^3; Athanasiadis,[145] i= m(m-a)b; Hesehus,[146] i=b^m—1; Ruhmer,[147] R_o/R_b= $(b/a)^a$; Stebbins, i=cm. (See Brown, Phys. Rev., 1911, *33*, pp. 1-26.) Brown states that although the illumination used, time of exposure, and construction of cell varied in the work of the above men, it appears obviously futile from these results to look for a universal law of conductivity for the selenium cell as a function of intensity of illumination.

In summarizing the difficulties that apply to the use of the

[140] Brown, F. C. Phys. Rev., 1914, *4*, Ser. 2, pp. 85-98; see also Dietrich, *ibid*, p. 474.

[141] Rosse. Phil. Mag., 1874, *47*, Ser. 4, pp. 161-164.

[142] Adams and Day. *Op. cit.*, p. 318.

[143] Berndt, G. Phys. Z., 1904, *5*, pp. 121-124.

[144] Hopius. Jurn. Russk. Fisik Chimicesk. Obscestva, 1903, *35*, pp. 581-585.

[145] Athanasiadis, G. Ann. der Physik, 1908, *25*, pp. 92-98.

[146] Hesehus, N. A. Jurn. Russk. Fisik. Chimicesk. Obscestva, 1905, *37*, pp. 221-231; Phys. Zeit., 1906, *7*, pp. 163-168.

[147] Ruhmer, E. Phys. Zeit., 1902, *3*, pp. 468-474.

selenium cell in the measurement of light, the following points then may be noted. (1) The fatigue effects and the effects of previous exposure to light are so great that it is exceedingly difficult to keep the cell in a state of constant sensitivity (2) The amount of response is not only a function of the time of exposure to the light, but apparently rather complexly so. (3) There is not only selectiveness of response to wave-length but the amount of this selectiveness varies with the intensity of light, with the strength of the battery current, with the temperature of the cell and with humidity.[148] While there is a possibility of controlling the last three of this latter group of factors, there seems no way to deal satisfactorily for any wide use of the cell with the first, or what may be termed roughly a "Purkinje phenomenon." Because of this factor a calibration of the cell for wave-length for one intensity of light would not hold for all intensities, which would limit the use of the cell to the intensity of light for which it was calibrated or for ranges for which there is no change in relative sensitivity to wave-length. That is, any wide use of the cell would require both a wave-length and an intensity calibration in terms, for example, of the responses of the non-selective instruments. And (4) there seems to be no regular relation of the amount of response to the amount or intensity of light used even when the lights are of the same composition. At least according to Brown this is the conclusion that must be drawn from the work that has been done with white light. If this be true, the possibilities of use of the selenium cell as a radiometric instrument seem in general practice to be limited to the equalization of light intensities and this, unless correction factors are used, only in case the lights are of the same composition. In this regard its case is similar to that of the eye when considered as a possible radiometric instrument.[149]

[148] It will be remembered also that the intensity of the photo-electric currents that are set up by the action of light on selenium which are an important factor in the variability of action of the cell, are different for the different wave-lengths. This factor obviously can not be controlled and there seems no satisfactory calibration for it.

[149] In this lack of a simple relation between the amount of intensity of light and amount of response, the selenium cell again presents an analogy to

4. *Theories of the action of light on selenium.* It may be of interest to append here a brief account of the theories that have been advanced to explain the action of light on selenium. The change of resistance of selenium under the action of light has at various times been thought to be a heating effect, to be electrolytic in nature, to be electronic, or to be of chemical origin. The first view was held by Sale, Sabine and Moser. Sabine, for example, thought that the action is similar in character to that of a dielectric "more or less charged with conducting crystals." In such a case the light by its heating effect would modify the surface tension of the selenium, which modification would probably cause an expansion of its crystalline surface and this in turn would result in a closer contact among the superficial crystals. This view was disproved by the demonstration that the light effect of the different wave-lengths on selenium does not correlate with their heating effect.

The theory that the action is electrolytic was first proposed by Adams and Day. They did not claim that actual electrolysis takes place, however, but that the molecular structure or crystalline condition of the selenium is altered or modified by the action of a current of electricity in such a manner as to produce effects analogous to those which would occur if the selenium were an electrolyte and were actually decomposed by the current. Furthermore, they thought that the action of light falling on selenium is to promote crystallization and thus to diminish its resistance to an electric current, inasmuch as in changing to the crystalline state selenium becomes a better conductor of electricity. And as this crystallization is greatest in the exterior layers of the

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the eye. And as in case of the eye this relation has as yet proven incapable of mathematical formulation. Fechner in his attempt to give a mathematical expression of the relation between stimulus and response for sensation in general was only trying to do what a number have tried to do with regard to this reaction both of the selenium cell and the photographic plate. When one knows how signally the attempt to find an expression separately for either of these reactions has failed, one realizes still more clearly the *a priori* improbability of finding a single expression that will apply to the reactions of five sensory mechanisms so differently constituted as they seem to be.

selenium, a flow of energy from within outwards is produced which under certain circumstances appears to produce an electric current (the photo-electric current). Bidwell thought the action is really electrolytic, impure selenides having been used or selenides having been formed between the selenium and the metallic electrodes.

Bidwell's view was disproved by Pfund and later by Berndt, both of whom used purified selenium and carbon electrodes and got greater sensitivity to light with the purified than with the impure selenium. Pfund developed an electronic theory of the action, an explanation that had previously been suggested by Nagaoka. He considered the effect due to a resonance of the electrons in the atom under the action of light, causing explosions which lead to an increase in the number of conducting electrons. There is, moreover, a "critical depth" of penetration above and below which the action on selenium is less pronounced. This fact accounts for the selective response to wave-length of light, the maximum response being to that light which penetrates to the "critical depth"; also for the change in this selectiveness of response to wave-length with change of intensity of the incident light. This view is held also by Ries and Nicholson.

The chemical theory has been followed among others by Marc, Montén, Kruyt, Pochettino and Berndt. These men have obtained evidence that leads them to believe that there exist at least two forms of metallic selenium of widely different electrical resistivity, and they assume that illumination brings about a transformation from the less to the more conductive of the two.

Brown claims to have found and isolated three forms of selenium crystals. They are produced at different temperatures in the annealing process and possess different conductivity. These "crystal forms" have also a different selectivity of response to wave-length. In his opinion the character of the conductivity curves for the four known varieties of light-sensitive selenium can be explained by assuming the existence of three components in dynamic equilibrium under a given illumination, temperature, pressure and electrical potential difference. Any agency that changes

the conductivity of selenium is of such a nature that it alters the rate of interchange between these components.

F. The photo-electric cell.

The action of the photo-electric cell depends upon the effect of light on the capacity of certain metals to hold a negative charge of electricity. Knowledge of the action of light on the conduction of electricity goes back to the discovery by Hertz in 1887 that the incidence of ultra-violet radiations on a spark gap facilitates the sparking. This led to a general investigation of the effect of light on the conduction of electricity.[150] The discoveries which paved the way directly for the invention of the photo-electric cell were those pertaining to the effect of light on the electrical condition of certain metals. It was found, for example, that a zinc plate exposed to light becomes slightly positively charged; that a negatively charged plate becomes less negatively charged; and that a positively charged plate is not affected. Later studies showed that the electrical condition of all metals is changed to some extent by the action of light. Those affected most are, according to Elster and Geitel,[151] rubidium, potassium, alloy of potassium and sodium, sodium, lithium, magnesium, thallium, and zinc.

The essential parts of the photo-electric cell are as follows. There must be juxtaposed in a glass tube or vessel a negatively charged surface of the metal in question (the cathode) and a conductor or anode to receive the charge as it is lost by the cathode under the action of light. Connected in series with the cell is either an electrometer or a galvanometer. In some cases the inside of the cell is coated with the metal forming the cathode and a receiving wire is suspended in the cell. In others, the negatively charged metal is suspended in the cell and the body of the tube silvered on the inside serves as anode. The photo-

[150] See Hallwachs, W. Ann. der Phys., 1888, *33*, p. 301; Hoor, M. Repertonnière des Physik, 1889, *25*, p. 91; Righi, A. Comptes Rendus, 1888, *106*, p. 1349 and *107*, p. 559; Stoletow, A. *ibid.*, 1888, *106*, p. 1149, 1593 and *107*, p. 91; 1889, *108*, p. 1241; Physikalische Revue, Stuttgart, 1892, *1*.

[151] Elster, J. and Geitel, H. Nature, 1894, *50*, p. 451.

electric current may be measured in five ways: (1) by the rate of drift of an electrometer needle; (2) by the ballistic method or the measurement of the charge acquired in a definite exposure time by an electrometer connected with the cell; (3) by measuring the potential across the terminals of a high resistance in series with the cell; (4) by balancing the photo-electric current with a current variable in a known manner, by means of either an electrometer or a sensitive galvanometer; and (5) by the deflections of a sensitive galvanometer. Ives[152] commenting on these recommends the third method. He finds the first inadvisable because the rate of drift is not uniform; the second, because the deflection varies with the exposure time; and the fifth, because it is insensitive.

1. *Factors that have been taken into account in the construction and use of photo-electric cells.* The following are some of the factors that have been taken into account in the construction and use of sensitive cells.

a. *The metal used.* The metal used should have a high emissive power and should permit of a certain ease in handling. Different metals have been used by different experimenters. Compton and Richardson,[153] for example, used aluminium, platinum, sodium and caesium. Potassium and sodium have been most frequently employed. For a summary of the metals used by different investigators, see Allen, Photo-electricity, 1913, p. 68.

b. *The residual gas.* It is desirable of course to have for the residual gas one which ionizes easily but not to such an extent that the recombination of the ions is measurable, also one which is easy to handle. Elster and Geitel[154] tested the rate of loss of charge from an illuminated surface through air, carbon dioxide, oxygen and hydrogen; and found that the rate of leak through carbon dioxide was much faster than for any of the other gases. Hydrogen, helium or argon have been most frequently used in the more recent work with photo-electric cells.

[152] Ives, H. E. Astrophys. Jour., 1914, *39*, p. 428.

[153] Compton, K. T. and Richardson, O. W. Philos. Mag., 1913, *26*, Ser. 6, p. 561.

[154] Elster, J. and Geitel, H. Ann. der Phys., 1890, *41*, p. 166.

c. *The pressure of the residual gas.* There are two factors here which work against each other. If we consider the current from the cathode to the suspended loop of wire as the discharge of negative electrons from the cathode, a vacuum would offer the least impedance. An advantage is gained, however, by adding to the electrons sent off by the metal, electrons freed by ionizing the gas in the tube. The effect of pressure on the intensity of the photo-electric discharge has been investigated by Stoletow,[155] Schweidler[156] and Kemp[157] by comparing the intensity of the current for different pressures under otherwise constant conditions. For Stoletow the most favorable range of pressures is from 0.275-2.48 mm.; for Schweidler, from 1-2 mm.; for Kemp, from 2-3 mm. In a recent work Ives, Dushman and Karrer[158] found that the pressure giving the greatest sensitivity varies with the voltage; further that the "photo-electric sensitiveness does not disappear when the metal is made as gas-free as possible and the degree of vacuum is made as high as possible."

d. *The potential difference between anode and cathode.* There must be a sufficient difference of potential between anode and cathode to guarantee that all of the electrons are drawn to the anode, *i.e.,* there must be a saturation difference of potential. The difference must not, however, be so great as to cause sparking, and it must be kept fairly constant. From about 20 to 180 volts are generally used. For an investigation of this effect, see Stoletow[159] and Schweidler.[160]

e. *The galvanometer or electrometer.* The electrometer is more sensitive than the galvanometer, but it is so much harder to manage that it seems to be the general opinion that it should be used only for measuring very low intensities.[161]

[155] Stoletow, A. Comptes Rendus, 1888, *107*, p. 91; J. de Phys., 1890, *9*, p. 468.

[156] Schweidler, E. R. Sitzungsber. der Wien. Akad., 1898, *107*, 2a, p. 881.

[157] Kemp, J. G. Phys. Rev., 1913, *1*, Ser. 2, p. 274.

[158] Ives, Dushman and Karrer. Astrophys. Jour., 1916, *43*, p. 9.

[159] Stoletow, A. Comptes Rendus, 1889, *108*, p. 1241.

[160] Schweidler, E. R. *Loc. cit.*

[161] See Richtmyer, F. K. Transactions Illuminating Engineering Society, 1913, *8*, p. 461.

f. *The angle of the incident light.* Elster and Geitel[162] first reported that the angle at which the light strikes the cathode plate causes a difference in the effect on the plate. This effect has been investigated among others by Pohl[163] and Kunz.[164] Elster and Geitel claim to have overcome the effect due to angle of incidence by using a diffusing screen so that the light falls equally at all angles on the plate.[165] Pohl and Pringsheim[166] have found in addition that the curve of selective response to wave-length of the photo-electric cell varies with the angle of incidence.

g. *Dark effects and after-effects.* When a cell is charged and left in the dark, a slight leakage or discharge is found to take place which is increased following an exposure to light. This leakage Elster and Geitel[167] believe to be due to a conduction of current over the surface of the glass from the cathode to the anode circuit. In any event guard rings of metal connected to earth, placed on the inside and outside of the tube between the cathode and anode circuit, completely eliminated the leakage.

h. *Fatigue effects.* Some metals when freshly prepared throw off many electrons when acted upon by light, then the number becomes less. This decrease in the responsiveness of the metal is apparently rapid at first, then becomes slower, ceasing perhaps in a few days. Allen,[168] for example, measured the photo-electric activity at different intervals from 2 to 100 minutes after polishing the surface of a zinc plate. He found a decrease in activity which was rapid for the first few minutes, then more gradual after 20 to 30 minutes. Sadzewicz[169] reports a similar result. The effect has also been investigated by Holman,[170] Hallwachs,[171]

[162] Elster, J. and Geitel, H. Wied. Ann. der Phys., 1894, *52*, p. 433; 1895, *55*, p. 684; 1897, *61*, p. 445.
[163] Pohl, R. Phys. Z., 1909, *10*, p. 542.
[164] Kunz, J. Phys. Rev., 1909, *29*, p. 174.
[165] Elster, J. and Geitel, H. Phys. Z., 1912, *13*, p. 740.
[166] Pohl, R. and Pringsheim, P. Deutsch. Phys. Gesell., 1910, *12*, p. 215.
[167] Elster, J. and Geitel, H. Phys. Z., 1913, *14*, p. 741.
[168] Allen, H. S. Proc. Roy. Soc., 1907, *78*, Ser. A., p. 483.
[169] Sadzewicz, M. Acad. Sci. Cracovie, Bull., 1907, *5*, p. 497.
[170] Holman, W. F. Phys. Rev., 1907, *25*, p. 81.
[171] Hallwachs, W. Ann. der Phys., 1907, *23*, (4), p. 459.

Compton and Richardson,[172] Buisson,[173] Ladenburg[174] and Bergowitz.[175] Bergowitz claims, however, that there is no fatigue in case of cells whose negative poles are formed of alkali metals. This statement is confirmed by Elster and Geitel[176] who say: "sogenannte 'Ermüdungserscheinungen' an Alkalimetallzellen nicht auftreten." Ives, Dushman and Karrer, however, apparently found fatigue effects in potassium cells.

2. *Comparative advantages and disadvantages of the photo-electric cell.* The photo-electric cell has the advantage of comparatively high sensitivity. To offset its sensitivity, however, it has the following serious disadvantages. (a) It is selective in its response to wave-length. The shorter wave-lengths are overestimated. This selectiveness moreover, varies with the metal used in the cell. Pohl, and Pohl and Pringsheim have plotted the curves of response to wave-length for the following metals: mercury,[177] platinum and copper,[178] potassium-sodium alloy,[179] rubidium, potassium and sodium,[180] barium, [181] lithium and sodium,[182] magnesium and aluminium,[183] and calcium.[184] The selectiveness for calcium is found to be very similar to the selectiveness of the eye to wave-length. Richtmyer has plotted the curve for sodium;[185] Hallwachs for potassium;[186] Kunz for sodium-potassium alloy;[187] and Elster and Geitel for

[172] Compton, K. and Richardson, O. Philos. Mag., 1913, *26*, Ser. 6, p. 561.
[173] Buisson, A. Comptes Rendus, 1900, *130*, p. 1298; Ann. Chim. Phys., 1901, *24*, p. 320.
[174] Ladenburg, E. Ann. der Physik, 1903, *12*, p. 558.
[175] Bergowitz, K. Phys. Z., 1907, *8*, p. 373.
[176] Elster and Geitel, H. Phys. Z., 1913, *14*, footnote p. 742.
[177] Pohl, R. Phys. Gesell. Verh. 1909, *11*, p. 609.
[178] Pohl, R. *Ibid.*, 1909, *11*, p. 339.
[179] Pohl, R. *Ibid.*, 1909, *11*, p. 715; Pohl and Pringsheim; *Ibid.*, 1910, *12*, p. 215, 349, 682, 697.
[180] Pohl and Pringsheim. *Ibid.*, 1910, *12*, p. 1039; 1911, *13*, p. 219.
[181] Pohl and Pringsheim. *Ibid.*, 1911, *13*, p. 474.
[182] Pohl and Pringsheim. *Ibid.*, 1912, *14*, p. 46.
[183] Pohl and Pringsheim. *Ibid.*, 1912, *14*, p. 546.
[184] Pohl and Pringsheim. *Ibid.*, 1913, *15*, p. 111.
[185] Richtmyer, F. K. Phys. Rev., 1910, *30*, p. 385.
[186] Hallwachs, W. Ann. der Phys., 1909, *30*, (4), p. 593.
[187] Kunz, J. Phys. Rev., 1909, *29*, p. 212.

rubidium, potassium and sodium.[188] (b) Griffith[189] working with ultra-violet light, and Dember[190] working with the visible spectrum, both claim that it is also selective in its response to intensity. That is, they do not find a constant relation between intensity of radiation and photo-electric current. Elster and Geitel,[191] however, found on the other hand a constant relation between intensity of light and the response of the cell except in case of very intense light. As source they used the light of the sun, a mercury arc, a Nernst lamp of 32 cp. and a 2-volt carbon lamp. A variable resistance was used with the 2-volt lamp; also in a part of the work its light was passed through a blue filter. Richtmyer[192] found the photo-electric current from a sodium surface under the action of light from an incandescent lamp to be proportional to the intensity of the incident light for very low intensities (0.007 candle-foot) up to 620 candle-feet. Ives in 1914 found that the relation between illumination and photo-electric effect is not linear and differs from cell to cell. In 1916, however, working with Dushman and Karrer he reports that the cause of these varied relationships lies in "focusing effects." "By this term is meant a change of direction of the electron stream as the number emitted changes, whereby a different proportion of the whole number of electrons reaches the receiving electrode" (p. 25). For the elimination of these effects he recommends a cell of special construction having absolutely no free surfaces on which electric charges can collect (see p. 30). This cell, he finds, gives a rectilinear relationship between intensity of illumination and photo-electric effect.[193] (c) The cell is not sensitive to

[188] Elster and Geitel. Ann. der Phys., 1894, *52*, (3), p. 438.
[189] Griffith, I. Phil. Mag., 1907, *14*, (6), p. 297.
[190] Dember, H. Ber. d. kgl. sächs. Akad. d. Wiss., 1912, *64*, p. 266.
[191] Elster and Geitel. Phys. Z., 1913, *14*, p. 741; 1914, *15*, p. 610.
[192] Richtmyer, F. K. Phys. Rev., 1909, *29*, p. 71, 404.
[193] Kunz recently reports an investigation of cells of special construction the responses of which to white light for a wide range of intensities deviates so little from a linear function of intensity of light as to permit of the use of the cell for many photometric purposes. He verifies Ives's claim that in case of the older spherical form of cell, the photo-electric current is not proportional to the intensity of light. He found also that the Talbot-Plateau law holds for the responses of the cells described. (Astrophysical Jour., 1917, *45*, pp. 69-88.)

heat radiations, hence can not be calibrated against the total of radiation of a black body. The value of its responses in terms of energy units can be determined feasibly and conveniently only by the aid of some other radiometric instrument which responds to the total of radiation, *e.g.*, the thermopile, the bolometer, the Nichol's radiometer, etc. (d) With the present knowledge and control of the factors which influence its sensitivity, the cell can scarcely be recommended as giving results with a degree of reproducibility which is entirely satisfactory. Thus from the standpoint both of reproducibility and selectiveness of response the use of the cell in its present stage of development even as an energy comparator of the visible radiations can scarcely be considered as advised by the radiometric specialist. However, the cell is still being developed and perfected and may yet be of service in measuring light intensities.

As a light measuring instrument the photo-electric cell has the following advantages. (a) It has a comparatively high sensitivity especially to the shorter wave-lengths.[194] And (b) it responds very quickly to the light stimulus. Richtmyer claims, for example, that one of the special fields in which the cell promises to be serviceable is for exposures too short for the eye to be used with accuracy and convenience.[195]

G. The photographic plate.

1. *The blackening of the plate and the factors which influence this action.* When light acts on a photographic plate a chemical change takes place in the sensitive film which renders it opaque to light when the plate has been developed. This is called the blackening of the plate, and is the response that must be calibrated if the plate is to be used as a light-measuring instrument. Unlike

[194] The shape of the curve representing the photo-electric response to wave-length is for calcium very similar to that of the eye. The maximum for most of the other metals that have been investigated, occurs much nearer to the violet end of the spectrum. The position of this maximum, as has been stated above, depends on the kind of metal used to give the photo-electric effect.

[195] Richtmyer claims advantage for the cell only in certain special fields of work. (See. Trans. Illuminating Eng. Soc., 1913, *8*, p. 459.)

the thermopile, for example, which gives its maximum response when once a thermal equilibrium has been attained and is from then on practically independent of the time of exposure to the light, the blackening of the photographic plate is a function of the time of exposure to the light as well as of its intensity and wavelength. An important problem in calibrating has been, therefore, to find out whether the amount of blackening sustains any regular relation to these two factors. If so, the relation can be expressed in terms of a formula; if not, the calibration must at every point be empirical. With regard to the degree of regularity of the blackening there has been a great deal of disagreement. In 1862, for example, Bunsen and Roscoe announced that the blackening may be expressed by the formula $S=i\ t$, in which S represents the blackening, i the intensity of light and t the time of its action on the plate.[196]

[196] That equal amounts of blackening are always produced by equal intensities of light and equal times of exposure was first accepted as a theoretical principle by Malaguti (Ann. de Chemie et de Phys., *26*, p. 5; Pogg. Ann. der Phys., 1840, *49*, p. 567).

It was first experimentally demonstrated within a narrow range of light intensities (1 to 2½ in an arbitrary scale) by Hankel (Abhandl. der k. Sächs. Gesell. d. Wiss. z. Leipzig, 1864, 9, p. 55). Its first claim to establishment as a general law came from Bunsen and Roscoe (Annal. der Phys. und Chemie, 1862, *117*, pp. 529-562). They say: "So wird man den Satz als feststehend betrachten dürfen, dass innerhalb sehr weiter Gränzen gleichen Producten aus Lichtintensität und Insolationsdauer gleiche Schwärzungen auf Chlorsilberpapier von gleicher Sensibilität entsprechen." The law may be applied under the following conditions. "(1) Wenn die bei Messungen des gesammten Himmelslichts in Betracht kommenden Lichtstärken nur noch von so kurzen Inductionsphänomenon begleitet sind, dass die dadurch erzeugten Störungen innerhalb der erlaubten unvermeidlichen Beobachtungsfehler fallen; (2) wenn es möglich ist, eine photographisch sensibele Schicht von völlig constant Empfindlichkeit darzustellen; (3) wenn sich eine unveränderliche, zu jeder Zeit und an jedem Orte leicht wieder hervorzubringende Schwärzung finden lässt, die eine sichere Vergleichung mit einer photographisch geschwärzten Fläche zulässt."

The first suggestion that photographic action may be used as a means of measuring light intensities seems to have come from Sir J. F. W. Herschel who describes an "actinograph or self-registering photometer for meteorological purposes" in Section VIII of paper "On the Chemical Action of the Rays of the Solar Spectrum on Preparations of Silver and other Substances, both metallic and non-metallic, and on some Photographic Processes (Philos. Trans., 1840, *130*, pp. 1-61); and suggests on pp. 46-47 that the photographic

This statement that the effect of the light on the plate may be expressed by the product of the intensity and time of exposure or is directly proportional to the energy of the light incident on the plate, has become widely known in the subjects of Chemistry and Physiology as the Bunsen-Roscoe law. If it were true that the blackening is proportional to the energy falling upon the sensitive surface, the photographic plate could be used directly as an energy measurer and would serve as an exceedingly useful means of measuring light intensities, for it has the additional advantages of great sensitivity and of integration of action through an interval of time. More recent investigations of the blackening, however, beginning with Abney in 1874,[197] give little support to the law formulated by Bunsen and Roscoe. The blackening does not vary regularly with the intensity and time of exposure for any considerable range of intensities and times of exposure. It is also, as is well-known, selective in its response to wave-length and this selectiveness varies with the intensity of the light. That is, like the eye the photographic plate is selective in its response to intensity (a crude analogy to the Purkinje phenomenon) and is irregular in its action through an interval of time.[198] Moreover,

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plate may be used to measure light. Later A. Claudet describes the "photographometer, an instrument for measuring the intensity of the chemical action of the rays of light on all the photographic preparations, and for comparing with each other the sensitiveness of these different preparations" (Philos. Mag., 1848, Ser. 3, *33*, pp. 329-335). Claudet also refers to T. B. Jordan who invented an instrument which he called a heliograph consisting of a cylinder covered with sensitized paper placed parallel to the axis of the ecliptic, which turned to follow the sun. The object of this apparatus was to get the actinic value of the sun's rays at different times in the day. The instrument was improved by R. Hunt in 1845 and called by him an actinograph. In the work of these men we find the somewhat obscure beginnings of the subject of actinometry which is later to compete with photometry and radiometry as methods of measuring light intensities.

[197] Abney, W. deW. Philos. Mag., 1874, *48*, Ser. 4, pp. 161-165.

[198] In addition to the above three characteristics crudely analogous to the eye, the action on the photographic plate is said by Bunsen and Roscoe to show an inertia or lag in coming to its full value. (See Pogg. Annal., 1855, *100*, p. 481-516; also Photochem. Untersuch., Ostwald's Klassiker, *34*, p. 363.)

The analogy in the response of the photographic plate to the optical Purkinje phenomenon was first mentioned by Miethe, Zur Aktinometrie astronomisch-photographischer Fixsternaufnahmen, Göttingen, 1889. The

the response varies with other factors which are in practice difficult to control and exceedingly troublesome if not impossible to take into account in the derivation of formulae.[199]

The tendency in fact among recent investigators has been to question whether a mathematical expression can be given to the action for any considerable range of intensities and times of exposure and to disagree widely with regard to the formula that should be used for the range of intensities and times of exposure regarded as most favorable to regularity of action. At different times the following formulae have been derived to express the action: $S=i\,t^p$ in which p represents a constant with a value of 0.86 (Schwarzchild);[200] $S=k.\ i\,t^p$ in which k and p are both constants (Leimbach);[201] $S=k.\log.\ i\,t^p$ (Parkhurst);[202] and $S=\log.(k.\ i^m\,t^n)$ in which k, m and n are all constants (Stark).[203]

The validity of the above formulae has been the subject of considerable experimental investigation. Renwick,[204] for example,

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phenomenon is discussed and tested experimentally within certain limits of difference in wave-length by Schwarzchild, (Sitzungsber. d. Wien. Akad., Math.-Naturwiss. Classe, 1900, *109*, 2a, pp. 1127-1135). Discussing the influence of the optical Purkinje phenomenon on the systematic differences in the different brightness catalogues of stars, he says: "Aber es besteht auch für die Photographie ein dem Purkinje-Phänomen ganz analoger Übelstand. Zwei verschiedenfarbige Lichtquellen, die bei einer gewissen, für beide gleichen Expositionszeit gleiche Schwärzung ergeben, erfüllen diese Bedingung nicht mehr, wenn mann die Expositionszeit ändert oder die Intensitäten der Lichtquellen im selben Verhältnisse verstärkt" (p. 1128).

[199] Blackening is said to vary with wave-length of light, with kind of plate, with process of developing, with intensity of light, with time of exposure, with temperature of plate, and with type of exposure—continuous or intermittent. With regard to type of exposure Abney (Journ. of the Phot. Soc., 1893-4, p. 63), Eder (Sitzber. d. Wiener Akad., Math-Nat. Classe, 1899, *108*, 2a, p. 1433), Englisch (Archiv. f. Wiss. Photog., 1899, 1, p. 117; 1900, *2*, p. 131), and Schwarzchild (Astrophys. Journ., 1900, *11*, pp. 92-100) all find a less effect with an intermittent than with a continuous exposure. Abney, for example, finds the retardation to be more pronounced the greater is the ratio of closed to open sector, the greater the speed of rotation employed, and the less the light intensity.

[200] Schwarzchild, K. Astrophys. Journ., 1900, *11*, pp. 89-92.

[201] Leimbach, G. Zeit. f. wiss. Photog., 1909, *7*, p. 174.

[202] Parkhurst, J. A. Astrophys. Journ., 1909, *30*, p. 33.

[203] Stark, J. Annal. der Phys., 1911, *35*, (4) pp. 461-486.

[204] Renwick, F. F. Photog. Journ.

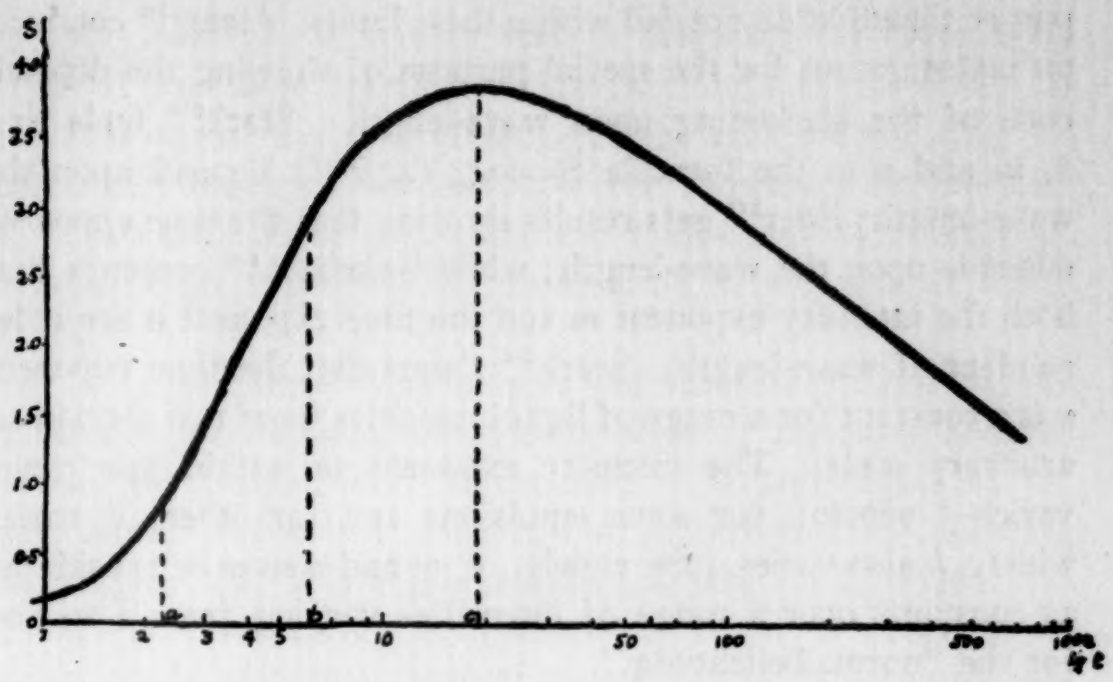


Fig. I.

contends that the Bunsen-Roscoe law falls short about 1.17 per-cent. Schwarzchild[205] finds for p a value of 0.86; while Tikhoff[206] claims that for the photographic rays p varies from 0.67 to 0.79; and for the green-yellow rays, from 0.91 to 0.96. Parkhurst[207] states that p is not a constant but a variable depending for its value (a) upon the density of the image, (b) the kind of plate used, and (c) the light filter employed. Geiger[208] finds that the law formulated by Schwarzchild is approximately correct within certain limits of time of action on the plate. Keeping the intensity the same and plotting the log. of the time against the blackening, Geiger obtains the curve given in Fig. 1. So plotted the curve should be a straight line according to the formula $S = i\, t^p$ if p is a constant. Between the points a and b the line is almost straight, he finds. Between these limits alone then the action is capable of approximate formulation, and the plate should not be used for light measurements for lengths of ex-

[205] Schwarzchild, K. *Loc cit.*

[206] Tikhoff, G. Mittheilungen d. Nikolai-Hauptsternwarte zu Pulkow, 1909, *31*, (3), p. 31; Comptes Rendus, 1909, *148*, p. 268.

[207] Parkhurst, J. A. Astrophys. Journ., 1909, *30*, p. 34.

[208] Geiger, L. Annal. der. Phys., 1911, *37*, (4) pp. 68-78.

posure time that do not fall within these limits. Abney[209] conducts an investigation for the special purpose of showing the dependence of the blackening upon wave-length. Stark[210] finds that *k*, *m* and *n* in the formula S=log. (k. $i^m t^n$) depend upon the wave-length; Eder[211] gets results showing that the time exponent depends upon the wave-length; while Leimbach[212] contends that both the intensity exponent *m* and the time exponent *n* are independent of wave-length. Stark[213] claims that the time exponent *n* is a constant for a range of light intensities from 1 to 1600 in an arbitrary scale. The intensity exponent *m* within this range varies 5 percent. for some emulsions and for others it varies widely. *k* also varies quite widely. *k*, *m* and *n* may be considered as constants over a range of intensities varying from 1 to 100 for the "normalbelichtung."

2. *The possibilities of using the photographic plate in quantitative work.* While the above may be considered only as the briefest mention of the quantitative work that has been done on the blackening of the photographic plate, still it is enough to show that the plate can scarcely be considered as a feasible light-measuring instrument. Its quickness of response, its sensitivity, and especially its integration of action through an interval of time make it very valuable, however, for many kinds of scientific work in which quantitative comparisons are not important.

H. The eye.

1. *The two possibilities of using the eye in light measurements.* As an instrument for the measuring or comparing of light intensities, the eye may be regarded in two ways. (1) It may be used to rate and compare lights designed for its own service. In the production of illumination effects this is the work of photometry and should be done by the eye or some instrument calibrated to give results in terms of the response of

[209] Abney, W. deW. Proc. Roy. Sec., 1901, *68*, pp. 300-321.
[210] Stark, J. Annal. der Phys., 1911, *35*, (4), pp. 461-486.
[211] Eder, J. M. *Op. cit.*, p. 1473.
[212] Leimbach, G. Diss. Göttingen, 1909; Zeit. f. wiss. Photog., 1909, *7*, p. 257.
[213] Stark, J. *Loc. cit.*

the eye. And (2) it may be used in balancing the energies of lights of the same spectro-radiometric composition. Used as such it is one of the most sensitive of the energy-comparing instruments. It can not be used, however, to balance radiometrically lights differing in composition without elaborate calibration, because of the degree of selectiveness of its response to wave-length.[214]

2. *The comparative advantages and disadvantages of the use of the eye for balancing energies of light of the same spectro-radiometric composition.* When used to balance lights of the same spectro-radiometric composition, the eye has the following advantages. (a) It is highly sensitive, among the most sensitive of the light measuring instruments. (b) It is quick in its action, reaching its maximum of response in times variously esti-

[214] It is in fact our interest in making a quantitative determination of the selectiveness of this response both to wave-length and to intensity in all the ways in which the eye responds to its stimulus, that has led us to attempt to help bring about means of rendering energy measurements feasible for the work in psychological optics. Under this heading would come, for example, the investigation of the selectiveness of the eye's achromatic response both to wave-length and to intensity with its wide application to photometry and light specification; the selectiveness of the chromatic response; the selectiveness to wave-length and intensity shown in the rise and decay of both types of response; the selectiveness found in after-image and contrast response; etc. In fact neither the characteristics and possibilities of the eye as a measuring instrument nor its peculiarities as a sense organ can be definitely known without a common unit in terms of which to evaluate the different wave-lengths to which it gives response. It is, moreover, obvious that neither the unit nor method of measurement must in any way involve the peculiarities of the responses of the eye itself.

In this work our point of view is to investigate the responses of the eye just as the physicist investigates the responses of his instruments. Too frequently this investigation has received its direction from theories and doctrinal conceptions. Such investigations can not help but be narrow in their scope and are moreover apt to lead to wrong conclusions. Much more will be accomplished, we believe, by holding theoretical and doctrinal interests in abeyance for a time and to approach the study of the eye's responses with the broader purpose of finding out what they are from the purely descriptive point of view, using methods and technique designed for such a purpose and not for the confirmation or destruction of a theory. In any event the two points of view should be kept separate in the work of investigation, and in the evaluation of results it should be clearly recognized to what degree a result is the product of the method of working employed.

mated from 0.014 to 0.541 sec. And (c) it possesses great advantages in the ease and convenience with which it may be used. Its disadvantages are very similar to those of the photo-electric and selenium cells. (a) Like both of these instruments it is very selective in its response to wave-length and can not be used, therefore, as an energy comparator of lights differing in spectro-radiometric composition without elaborate calibration. (b) Like the selenium cell and photographic plate it is selective also in its response to intensity. It is perhaps more selective in this regard than the selenium cell. And (c) it responds only to the visible spectrum and can, therefore, be calibrated against a black body only with exceeding difficulty and with many chances of error both in the calibration and its subsequent use. (See preface, pp. vi-vii. If calibrated, the thermopile or some other instrument which is sensitive to the total of radiation would ordinarily be employed and the calibration be made in terms of its responses. The work of calibration presents, moreover, great difficulties in case of the eye because of the lack of a fixed or closely reproducible scale of responses capable of numerical rating which can be correlated with the responses of the calibrating instrument. Two possibilities for calibrating suggest themselves: (a) the determination of sensitivity curves, valid only for the particular eye, the exact physical and physiological conditions, etc. for which the calibration was made, and for ranges of intensity in which no changes in relative sensitivity occur; and (b) the correlation of a just noticeable difference series with the corresponding energy values for such parts of the spectrum as are most frequently used. Neither of these possibilities, it is obvious, would be of much service for any very wide use of the eye as a measuring instrument. It will be the work of later papers to show in detail the selectiveness of the eye's response to wave-length and to intensity.

III. A Convenient and Sensitive Radiometric Apparatus for Work in Psychological and Physiological Optics.

The radiometric apparatus which we have used in our work for the past four years consists of two thermopiles, a very

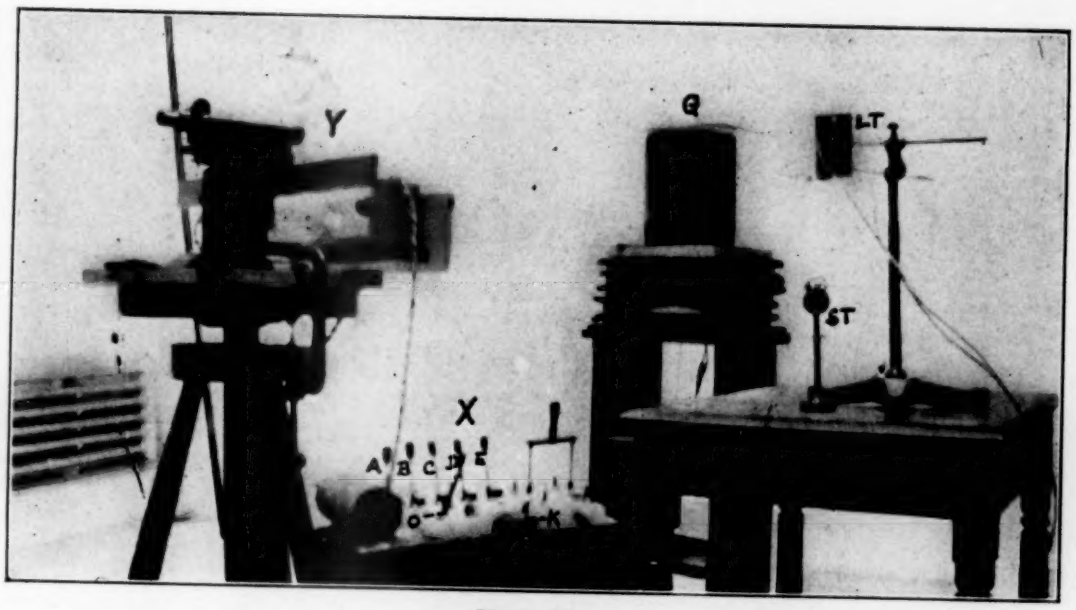


FIG. II

sensitive Thomson galvanometer and auxiliary apparatus for both thermopile and galvanometer. The two types of thermopile, the galvanometer, and the auxiliary apparatus for the thermopiles and galvanometer were constructed by Dr. W. W. Coblentz of the Radiometric Division of the Bureau of Standards. This apparatus is shown in Fig. II. LT is the linear thermopile in its brass mounting; ST is the surface thermopile; G is the galvanometer with its magnetic shields; X is the auxiliary apparatus for thermopile and galvanometer; and Y is the telescope and scale.

A. THE LINEAR THERMOPILE

We are at present using two types of thermopile, a surface and a linear pile. By using the two the energy of the light employed for the colored stimulus can be measured at three places: at the opening of the campimeter screen with the surface pile which has a receiving area just large enough to cover this opening; at the analyzing slit of the spectroscope with the linear pile; and at the eye also with the linear pile. The linear pile with a receiving surface of 2 x 12 mm. is broad enough to cover either the analyzing slit or the colored image of this slit in the plane tangent to the anterior surface of the eye. The linear pile measuring at the slit and at the eye would thus be adequate alone for our purpose. Some additional advantage is gained perhaps by having two instruments to serve as a check on each other and by measuring at three places instead of two.

The thermo-elements in both piles are of bismuth and silver. The linear pile consists of 20 elements joined in series. These elements are in the form of wire, the bismuth 0.1 mm. in diameter and the silver 0.051 mm. in diameter. The total resistance of the pile is 8.4 ohms; the area of the receiving surface is 2 x 12 mm. In Fig. III this thermopile is shown drawn to scale. In the lower right hand corner is shown a front view of the pile. The row of junctions in the center are the "hot" junctions or those exposed to the radiations to be measured. The rows on either side of this are the "cold" or unexposed junctions. Directly above is shown in detail the formation of a pair of "hot" and "cold" junctions. A bead of silver is used in welding the

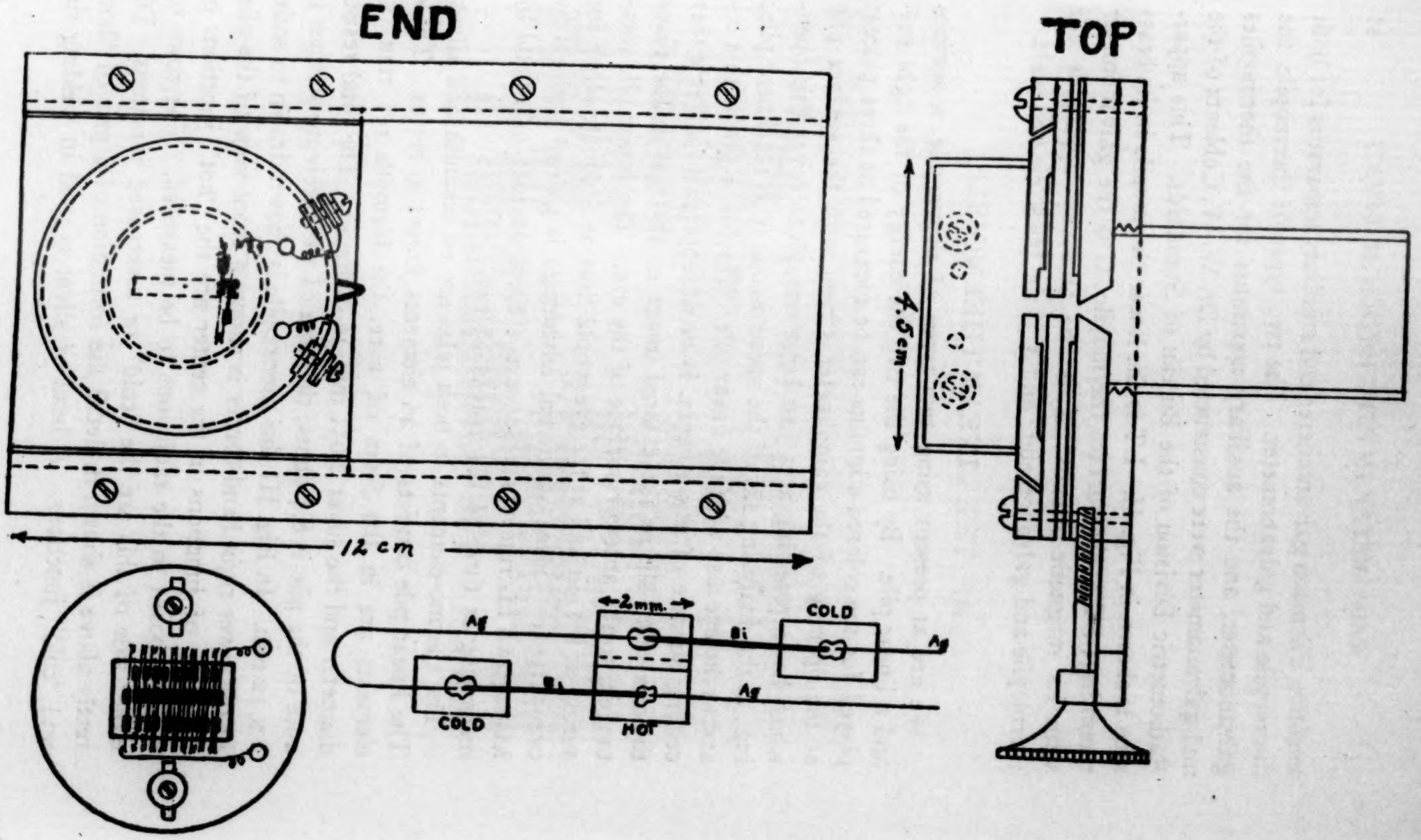


FIG. III

bismuth and silver wires together to form the junctions. Over each of the "hot" junctions is fastened a receiving surface of tin 2 mm. broad and long enough for the successive pieces to overlap. That the heat conducted to the "cold" junctions may rapidly radiate and thus maintain a temperature difference between the two junctions as large and as constant as possible, a surface of tin of appropriate size is fastened also over each of the "cold" junctions. In the diagram are also shown the top and end views of the pile mounted for use. The pile is mounted on a flat metal base which slides up and down in grooves constructed on the edges of the frame containing the analyzing slit for the spectroscope. When in use it is lowered so that the analyzing slit opens directly upon the face of the pile. During the color observation, when not in use, the pile is raised to the upper part of the frame clear of the slit, and is fastened by means of a small hook which engages the upper edge of the frame.

B. THE SURFACE THERMOPILE

This thermopile was designed especially for our work by Dr. Coblentz. The object was to get a thermopile that would measure directly all of the light that fell on the opening of the campimeter screen. This opening is 15 mm. in diameter. The surface of the thermopile was made 17 x 17 mm. The surface exposed to radiation was reduced to coincide with the stimulus-opening by means of a circular diaphragm 15 mm. in diameter. In order to shield the exposed junctions from the influence of air currents this aperture was covered with a thin sheet of clear glass (cover glass).

The pile consists of three units joined in parallel. Each unit consists of 20 elements, bismuth and silver wire, joined in series. The bismuth wire is 0.1 mm. and the silver wire is 0.051 mm. in diameter. The total internal resistance of the pile is 3.65 ohms. Each of the "hot" junctions is covered with a surface of tin, 6 x 1 x 0.02 mm. The "cold" junctions are to the rear of the "hot" junctions instead of on either side as is the case in the linear pile. That is, on leaving the "hot" junction, instead of running to either side each of the elements is bent backward. To

simplify the construction, the radiating surfaces of tin which cover the "cold" junctions in the linear pile were omitted from the surface pile.

A diagram of the surface pile is shown in Fig. IV. A shows the mounting for the ivory supports to which the sensitive elements are attached; B shows the way in which the wires are bent from the "hot" junctions to form the "cold" junctions; C gives

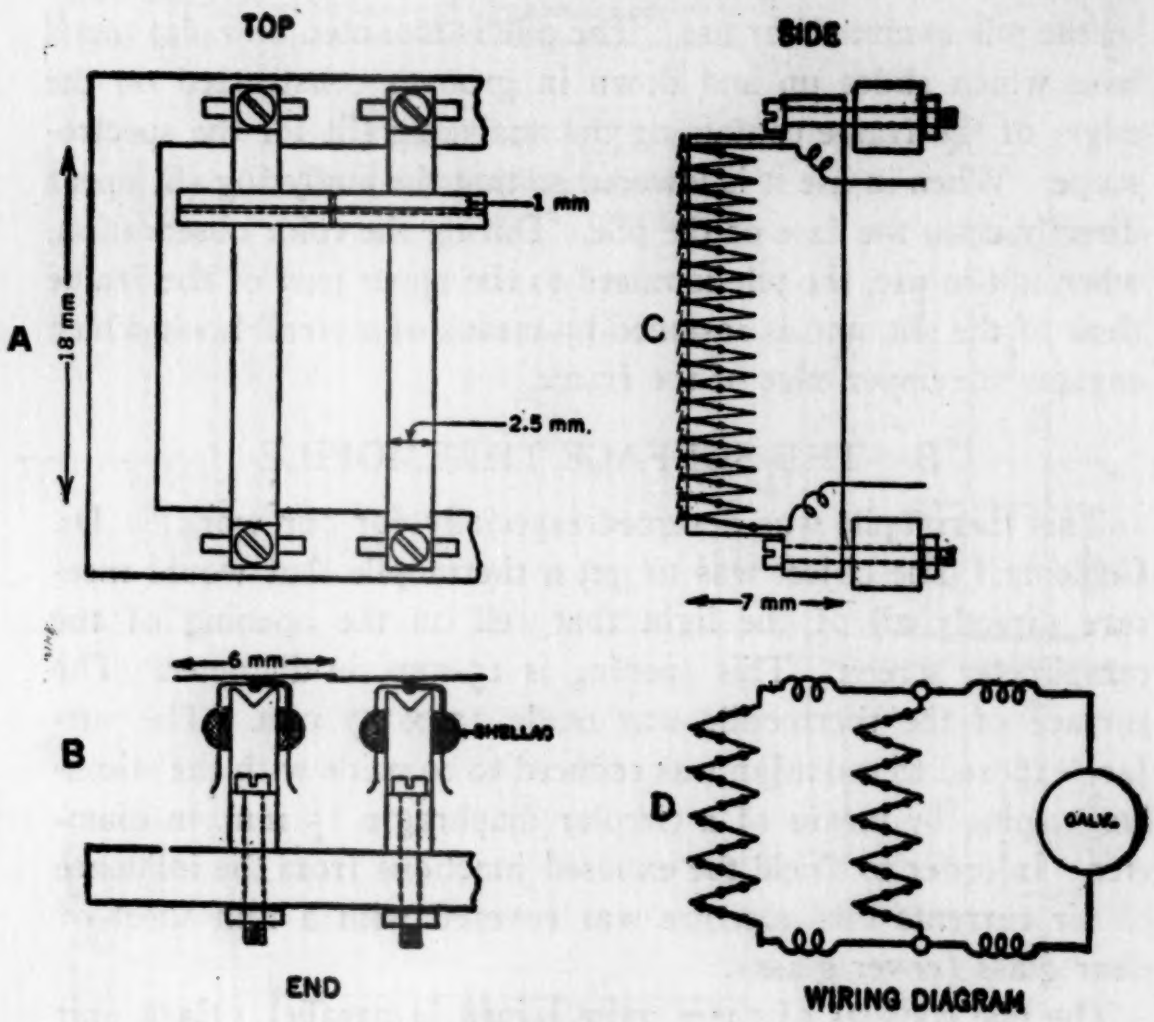
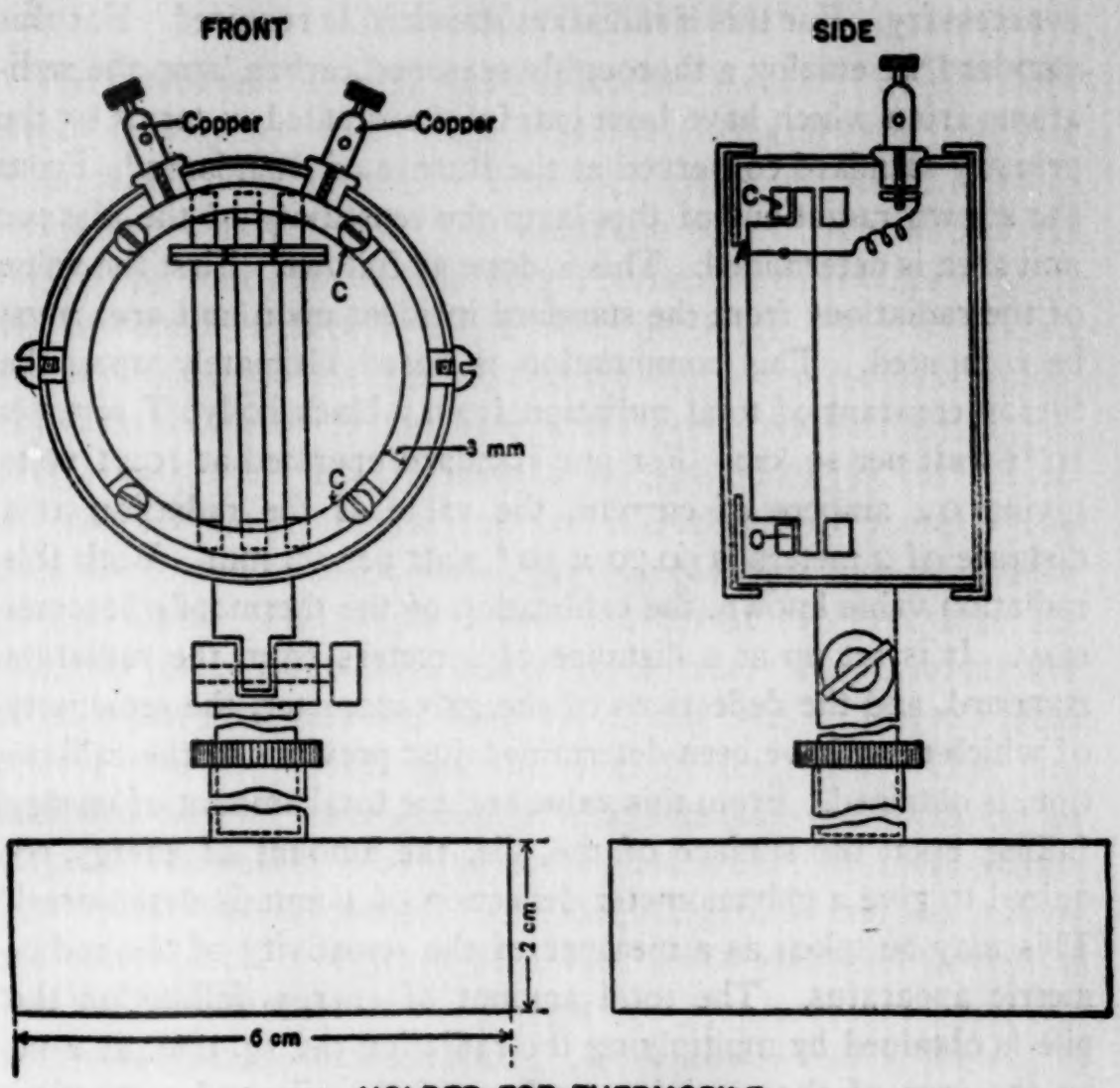


FIG. IV

a side view of one unit of the pile consisting of 20 thermo-elements mounted on the ivory support; and D shows the way in which the units are connected. In order to reduce the resistance and thus increase the sensitivity of the pile they are joined in parallel. In Fig. V are shown the front and side view of the holder for the thermopile.



HOLDER FOR THERMOPILE

FIG. V

In common with all surface radiometers of high sensitivity this surface thermopile causes some drift of the zero of the galvanometer unless the instrument and the shutter enclosing it are carefully protected from changes in temperature due to contact with the air of the room. Winding the terminals and body of the thermopile with cotton batting has overcome this effect almost entirely.

C. THE RADIATION STANDARD

The thermopile might be used for equalizing energies or reproducing given light intensities without calibration. However, if its responses are to be converted into C. G. S. units, calibration

is necessary. For this a radiation standard is required. For this standard we employ a thoroughly seasoned carbon lamp the radiations from which have been carefully evaluated in terms of the primary standard conserved at the Bureau of Standards.[1] From the known radiations of this lamp the sensitivity of the pile per unit area is determined. This is done as follows. First the value of the radiations from the standard incident upon unit area must be computed. This computation is based ultimately upon the Stefan constant of total radiation from a black body: $T = 5.7 \times 10^{-12}$ watt per sq. cm. For our standard operated at 102.1 volts giving 0.4 ampere of current, the value of the radiation at a distance of 2 meters is 90.70×10^{-8} watt per sq. mm. With this radiation value known, the calibration of the thermopile becomes easy. It is set up at a distance of 2 meters from the radiation standard, and the deflections of the galvanometer, the sensitivity of which must have been determined just previous to the calibration, is obtained. From this value and the total amount of energy falling upon the surface of the pile, the amount of energy required to give a galvanometer deflection of 1 mm. is determined. This may be taken as a measure of the sensitivity of the radiometric apparatus. The total amount of energy falling on the pile is obtained by multiplying the radiation per sq. mm. at 2 m. by the area of the receiving surface of the pile and correcting this value for the absorption of the glass cover (12% in case of our instrument).

Since the galvanometer sensitivity may vary from time to time, it is necessary to establish for it a standard of sensitivity and to reckon the radiation sensitivity of the apparatus in terms of the reading at this standard sensitivity. In order to use the value so established in future work with the apparatus, it is necessary to determine each time the current sensitivity of the galvanometer which is quickly done with an especially devised testing apparatus, and to compute from this and the standard sensitivity a correction factor which has to be applied to all readings taken at this time.

[1] Coblentz, W. W. Bull. Bur. Standards, 1914, 11, p. 87.

D. THE GALVANOMETER

The galvanometer used was constructed specially for the thermopile employed. It is of the Paschen small-coil type, shielded from magnetic influence by four cylindrical soft iron shields. Its parts are as follows. The magnetic field of the instrument is given by four coils each having a resistance of 6 ohms. Each coil is wound in three layers, 2 ohms per layer. The wire used was B & S gauge Nos. 38, 30, and 26, single covered silk insulation, the diameter of the bare wires being respectively 0.101, 0.255, 0.405 mm., and the lengths 92, 595, and 1375 cm. Each coil has a diameter of 2.8 cm. and a thickness of 7 mm. The coils are joined in pairs, series parallel, giving a total resistance of 6.58 ohms. The needle system consists of two groups of six magnets placed above and below the mirror. The magnets are of tungsten steel and are from 1.5 to 2.5 mm. in length; from 0.3-0.4 mm. in width; and 0.1 mm. in thickness. They are mounted so that each group of magnets has the form of an ellipse. The mirror is of thin cover glass 2 mm. x 3 mm., platinized by cathode discharge. The magnet groups and the mirror are mounted on a segment of a very small glass rod in such a way that the centers of the groups are 33.5 mm. apart and the mirror is midway between them. At the lower end of the rod is attached a damping vane of bolometer platinum 5 x 4 x 0.003 mm. The needle system weighing 12-15 mg. was made heavy to minimize the influence of earth tremors. It is suspended between the coils by means of an extremely fine quartz fiber.

The assembled galvanometer consisting of base provided with leveling screws, the coils and their ebonite supports, the needle system and the containing tube for its suspension, is drawn to scale in Fig. VI and needs little explanation. The coils, coated with paraffine to give the insulation needed, are attached to the ebonite supports by means of soft wax (a mixture of Venice turpentine and beeswax which hardens to the desired consistency on standing). Soft wax is used because it permits of an easy and convenient adjustment of the position of the coils, the faces of which should be brought to exact parallelism. This can

be done very conveniently by moving up and down between the faces of the coils a rectangular object of the proper width, *e.g.*, a microscope section glass. Having been rendered parallel the faces of the coil are brought into the vertical by means of the leveling screws on the base of the instrument. The quartz fiber which suspends the needle system passes through the containing tube and is attached at the top to a short brass pin with a milled head, held in place by means of a set screw. The needle system is fastened to the quartz fiber with shellac. The attachment of the needle system to the quartz fiber and this in turn to the brass pin is made on a special mounting board designed for the purpose. The housing of the galvanometer is of microscope section glass. This not only prevents disturbances of the needle system due to air currents but permits of an excellent illumination of the interior of the galvanometer.

The magnetic shielding[215] of the galvanometer consists of an inner laminated cylinder made up of six layers of transformer iron, 3½ inches in diameter, and three sections of soft iron pipe 5, 6 and 10 inches in diameter respectively, and 10 inches high. Each of these shields contains a horizontal window 1 cm. high and 8 cm. long through which the mirror is viewed. They rest on a slab of slate and a glass plate is put on top. Care is taken to keep the shields well annealed, but in spite of this some magnetism is acquired in handling. The influence of this and of the earth's field on the needle system has to be overcome if the galvanometer is to have the long period needed for a high current sensitivity. This might be done in two ways. (1) The unknown and very complex field due to the iron shields could be ascertained by means of control magnets; or (2) a stronger and simpler known field could be created and this field be weakened to the desired amount. The latter is found to be the more feasible procedure. The field is created by a short magnet placed under the base of the galvanometer in such a position that the mirror and its reflected

[215] For working in localities close to street cars and other magnetic disturbances, it is necessary to use a more thoroughly shielded galvanometer, the coils of which are imbedded in soft iron. See Bull. Bur. Standards, 1916, *13*, p. 423.

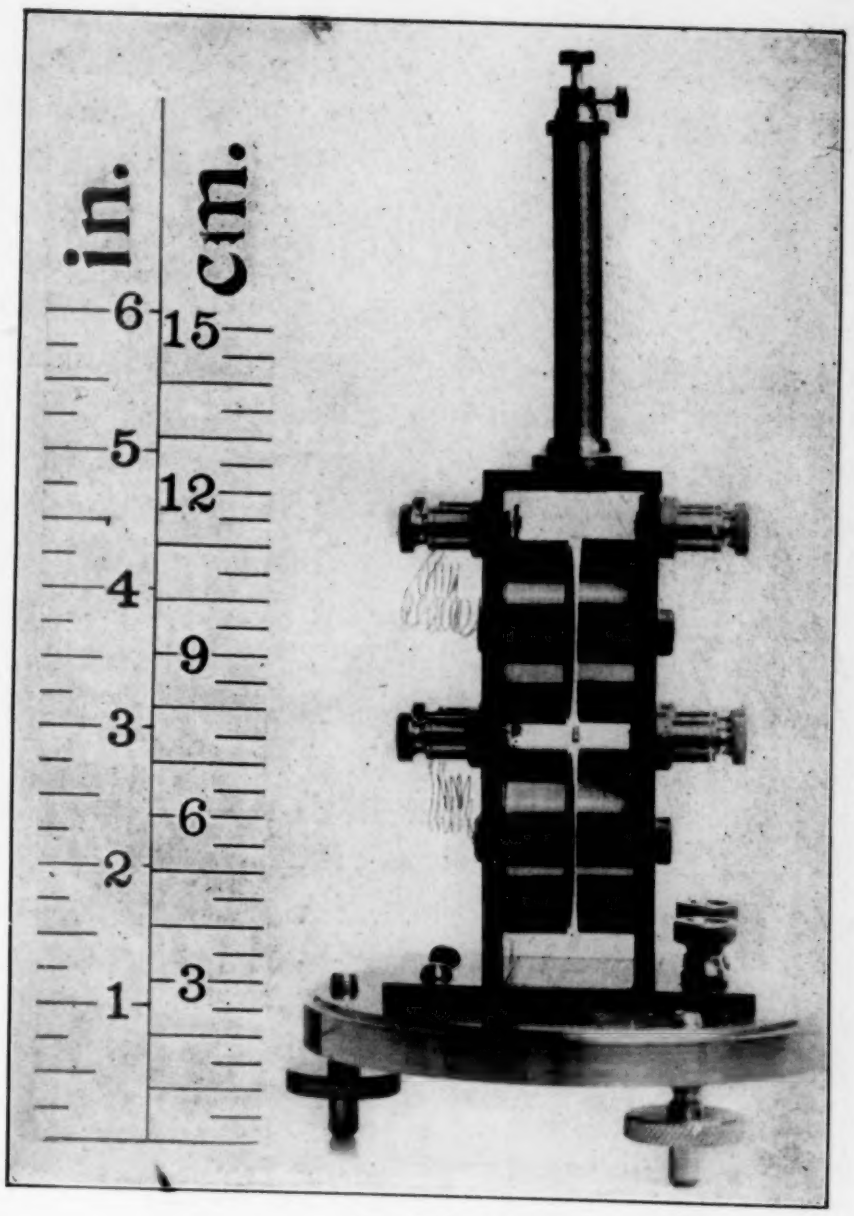


Fig. VI

scale are brought into the field of the observing telescope. This field is then weakened the desired amount by a larger magnet of greater strength placed on the glass plate covering the top of the shields. The large magnet is rotated about the vertical axis of the galvanometer until the needle which follows it passes quickly through a neutral point and rotates in the opposite direction. In this position of the magnets the effective field is not so great as the moment of torsion of the needle system, and the galvanometer should have a long period and a high current sensitivity.

E. THE AUXILIARY APPARATUS

This consists of a device for testing the sensitivity of the galvanometer, a set of resistance coils to cut down the throw of current from the thermopile, and a reading telescope and scale.

1. *The sensitivity tester for the galvanometer.* The sensitivity tester consists of a dry battery giving an E.M.F. of 1.43 volts, and of three shunt coils with the necessary switches mounted on a suitable base. The shunt coils have a resistance of 1000, 100 and 1000 ohms respectively and are designed to pass 1.43×10^{-8} ampere of current through the galvanometer. This divided by the number of scale divisions of the deflections produced gives the value of the current required to give a deflection of one scale division, or the sensitivity of the instrument. That is, the formula expressing the sensitivity is $i = \frac{1.43 \times 10^{-8}}{d}$, in which d is the number of scale divisions in the deflection; 1.43×10^{-8} is the total strength of the current; and i is the amount of current required to produce a unit deflection. For example, the galvanometer we use when adjusted to a 3 second period single swing gives a deflection of 40 scale divisions. This gives a sensitivity of $\frac{1.43 \times 10^{-8}}{40}$, or 3.575×10^{-10}.

The galvanometer may be connected either with the sensitivity tester or the thermopile by means of two-pole, double-throw knife switch, as is shown at x in Figure II. When connected with the shunt coils of the sensitivity tester, the circuit is closed with the

dry cell by means of a key shown at k. Sometimes when the galvanometer is adjusted to a high degree of sensitivity a big shift of the zero occurs when the double-throw switch is changed from the pole connecting the galvanometer with the sensitivity tester to the pole connecting it with the thermopile. This makes it necessary to readjust the magnets above the galvanometer to bring the zero again to the center of the scale. To avoid this a further means is provided for testing the sensitivity of the galvanometer without opening the switch which connects the thermopile with the galvanometer. This consists of an auxiliary coil of wire which is connected directly with the dry battery and a key to close the circuit, shown at o. This coil is mounted in a fixed position on the casing about the tube containing the suspension above the needle system. When a current is sent through the coil a deflection is given which is proportional to the current sensitivity of the galvanometer and in fixed ratio to the deflection that is produced when the same amount of current is sent through the shunt coils of the sensitivity tester to the galvanometer coils. This fixed ratio may be determined once and for all by closing each of these two circuits in turn with the dry cell and comparing the deflections produced.

2. *Special resistance coils.* The resistance coils designed to cut down the throw of current from the thermopile to the galvanometer are thrown into the thermopile circuit by means of a series of single-pole, single-throw knife switches shown at A, B, C, D, and E, Fig. I. When A is closed no resistance is added, the full current passes to the galvanometer, and the true deflection is produced. When, however, B, C, D, and E are closed, the current is made to pass through 10, 40, 100, and 191 ohms respectively, and the observed deflections must be multiplied by the following factors to give the true deflections: B=1.657; C=3.63; D=7.57; and E=13.55.

3. *The telescope and scale.* The telescope and scale used are of the kind ordinarily employed when precision is wanted in the reading of a sensitive galvanometer. The scale is graduated to millimeters and illuminated by two 40-watt tungsten lamps which can be moved along in front of the scale to give the maximum

illumination of the part of the scale reflected by the mirror. The telescope is fitted with a lens system that will permit the clear reading of the scale at a distance of 2 meters. At this distance the definition is such that the scale can be read to 0.5 mm.

We recommend to workers in psychological optics the apparatus described in the foregoing pages as feasible, adequately sensitive, and precise. We feel that especial acknowledgment is due to Dr. Coblentz for a notable contribution to the apparatus available for the more definitely quantitative work in the subject.